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Title: Biokinetic and Dosimetric Models

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Biokinetic and Dosimetric Models

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(November 2021)

Internal Dosimetry:
An Intersection of Disciplines

- Physiology,
- Anatomy,
- Physics,
- Mathematics,
- Computer Science,

- Some people call it “The art of Internal Dosimetry”!

Basic Components for Internal Dose Calculations

- Biokinetic (metabolic) models describing the intake, distribution, retention and excretion of radionuclides in the body.

  (Used to calculate the amount of total radioactive disintegrations inside the several body organs)

- Dosimetric models describing the interaction of radiation within the several body organs and tissues.

  (Used to calculate the doses in each "target organ" due to a single radioactive disintegration inside each individual "source organ")

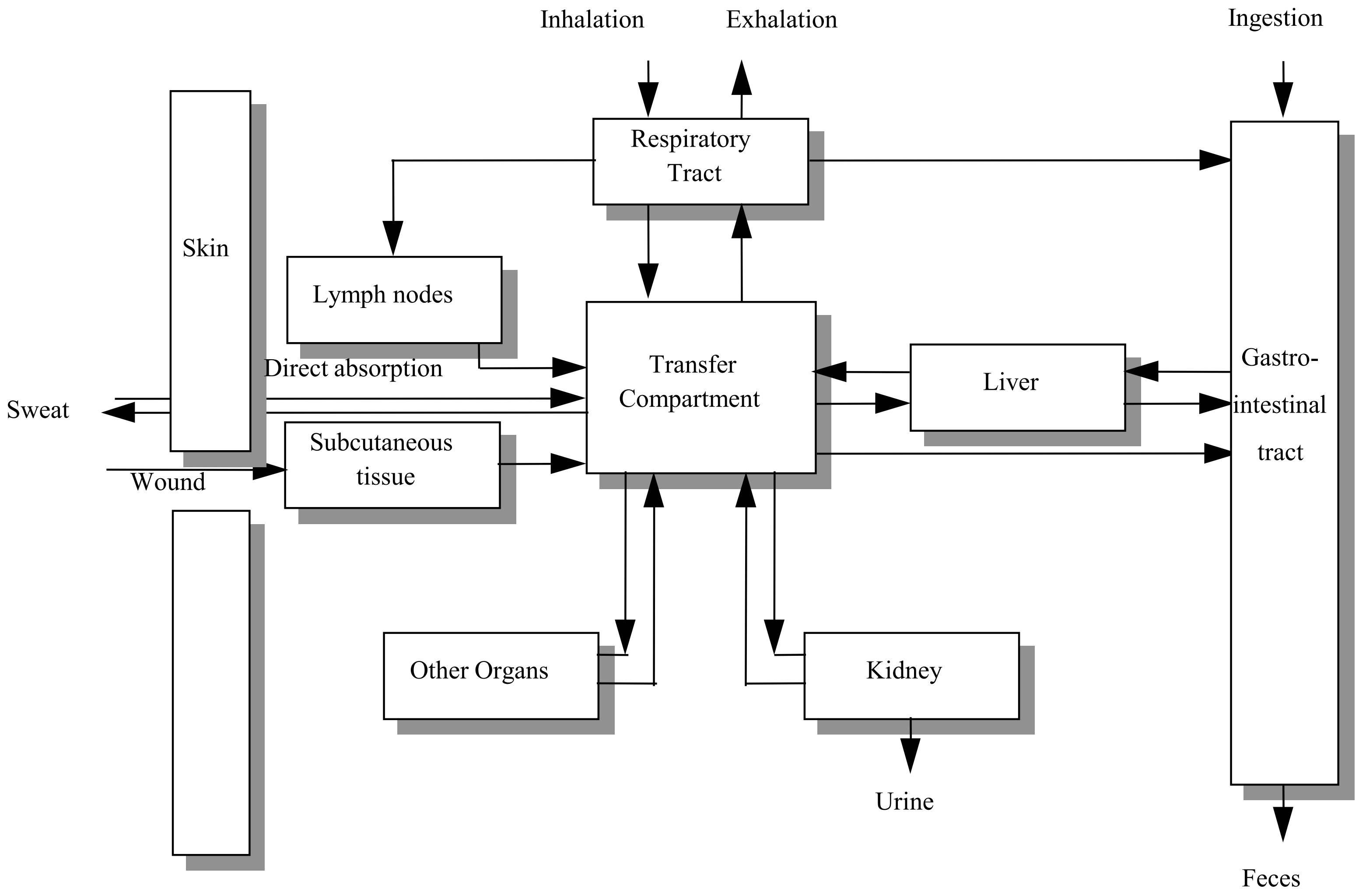
- System of dose limitation.

Reference Male and Reference Female
(Reference Individual)

An idealized male or female with anatomical and physiological characteristics defined by ICRP for the purpose of radiological protection.

Biokinetic Models and Their Evolution

A General Biokinetic Model Showing Routes of Intake, Transfers and Excretion



Evolution of the Respiratory Tract Models

ICRP Publication 2 (1959)

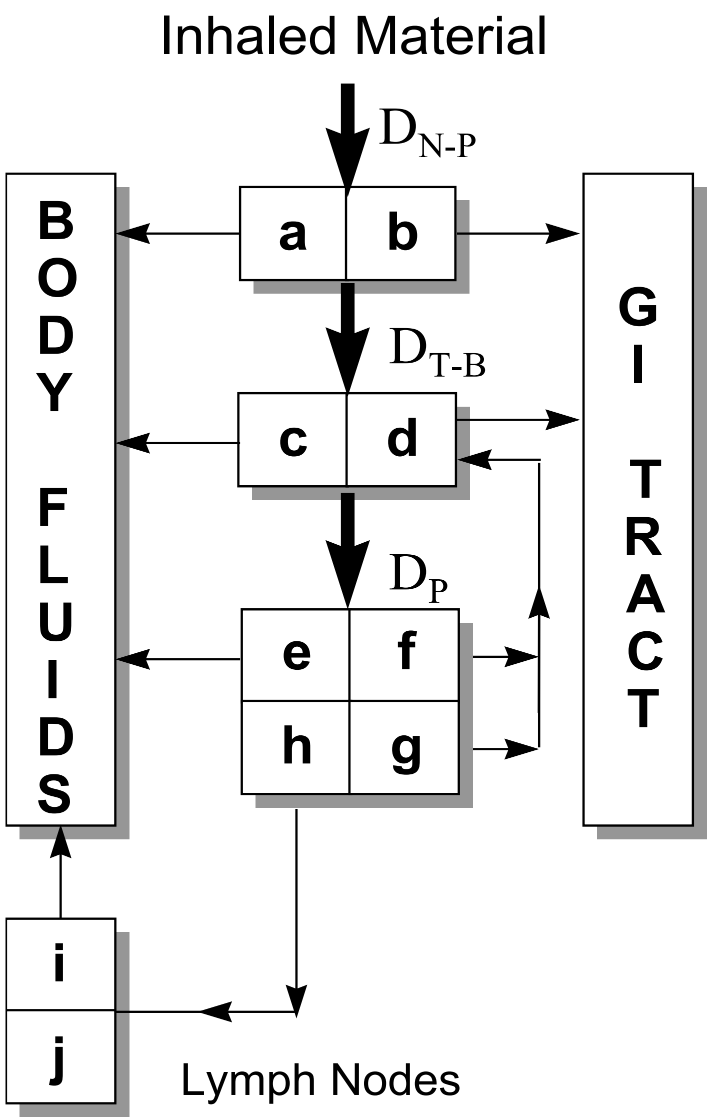
Table 10. Particulates in respiratory tract of the standard man

Retention of particulate matter in the lungs depends on many factors, such as the size, shape and density of the particles, the chemical form and whether or not the person is a mouth breather; however, when specific data are lacking it is assumed the distribution is as shown below.

Distribution	Readily soluble compounds (%)	Other compounds (%)
Exhaled	25	25
Deposited in upper respiratory passages and subsequently swallowed	50	50
Deposited in the lungs (lower respiratory passages)	25 (this is taken up into the body)	25*

* Of this, half is eliminated from the lungs and swallowed in the first 24 hrs, making a total of $62\frac{1}{2}$ per cent swallowed. The remaining $12\frac{1}{2}$ per cent is retained in the lungs with a half-life of 120 days, it being assumed that this portion is taken up into body fluids.

The ICRP Publication 30 Respiratory Tract Model (1979)



Deposition of particles:
Default: AMAD = 1 μm

Clearance: retention of compounds in pulmonary region.

- Class D: half-times < 10 days
- Class W: 10 < half-times < 100 days
- Class Y: half-times > 100 days

Health Physics Pergamon Press 1966. Vol. 12, pp. 173–207. Printed in Northern Ireland

DEPOSITION AND RETENTION MODELS FOR INTERNAL DOSIMETRY OF THE HUMAN RESPIRATORY TRACT*

TASK GROUP ON LUNG DYNAMICS

(*Received* 26 *July* 1965)

PREFACE

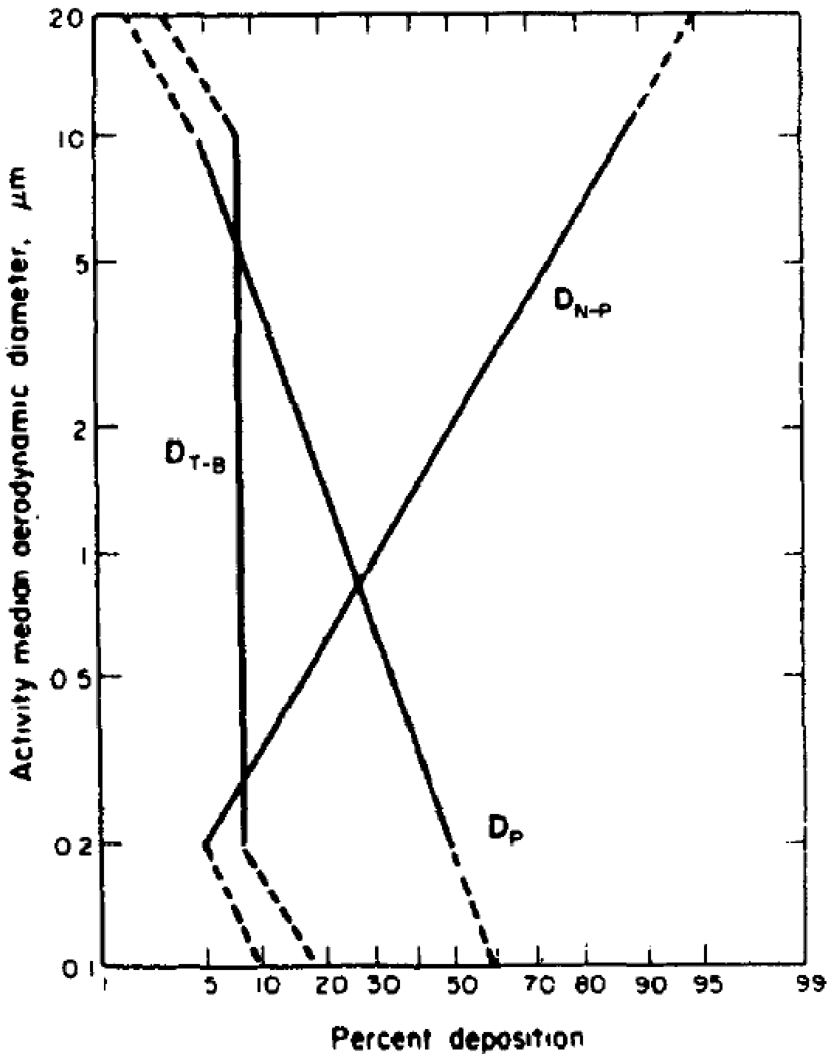
This report was prepared by the Task Group on Lung Dynamics for Committee II of the International Radiological Protection Commission. The Task Group consisted of the following members:

Dr. David V. Bates, Director, Respiratory

I. INTRODUCTION

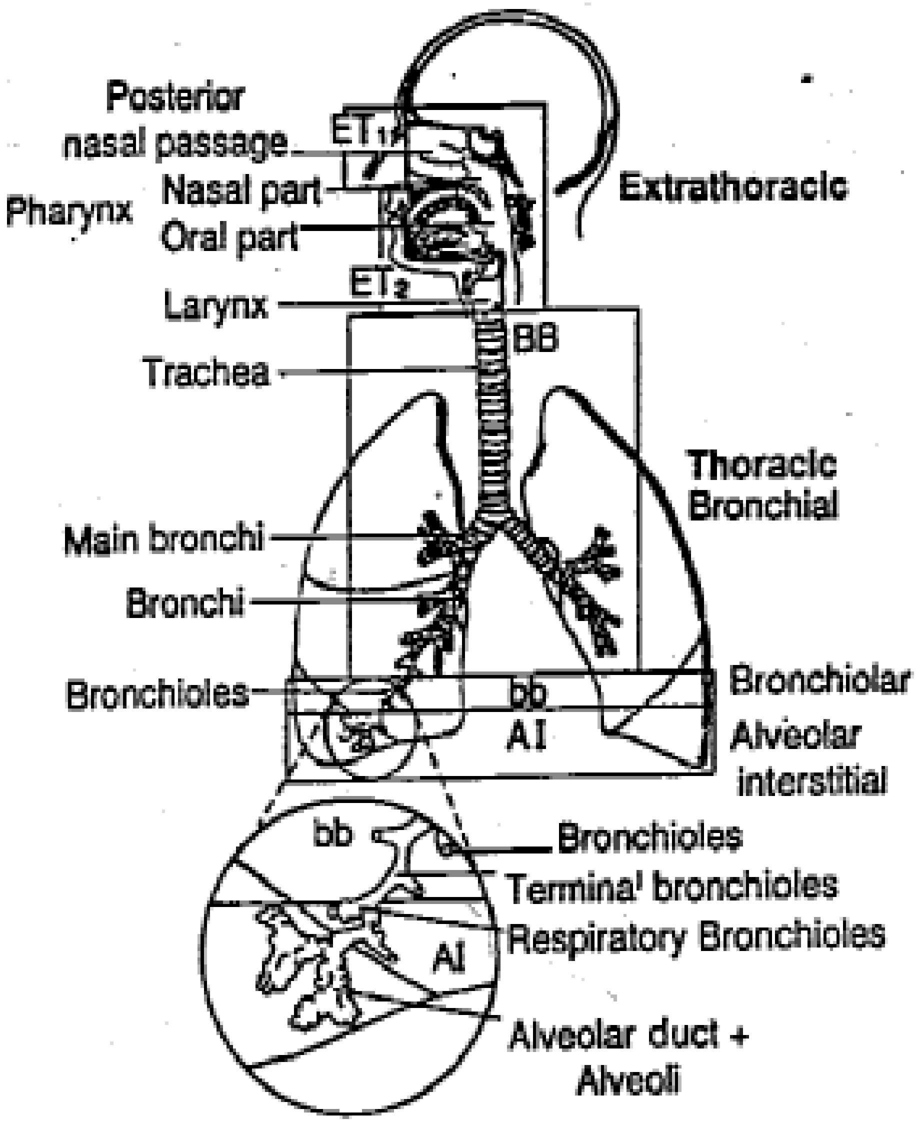
In 1964, ICRP Committee II created a special Task Group for the purpose of reviewing the so-called lung model,[1] a scheme for computing dust deposition in and clearance from the human respiratory tract thereby providing a basis for lung dosimetry and the setting of exposure limits.

Deposition of dust in the respiratory system. The percentage or activity or mass of an aerosol which is deposited in the N-P, T-B and P regions is given in relation to the Activity Median Aerodynamic Diameter (AMAD) of the aerosol distribution

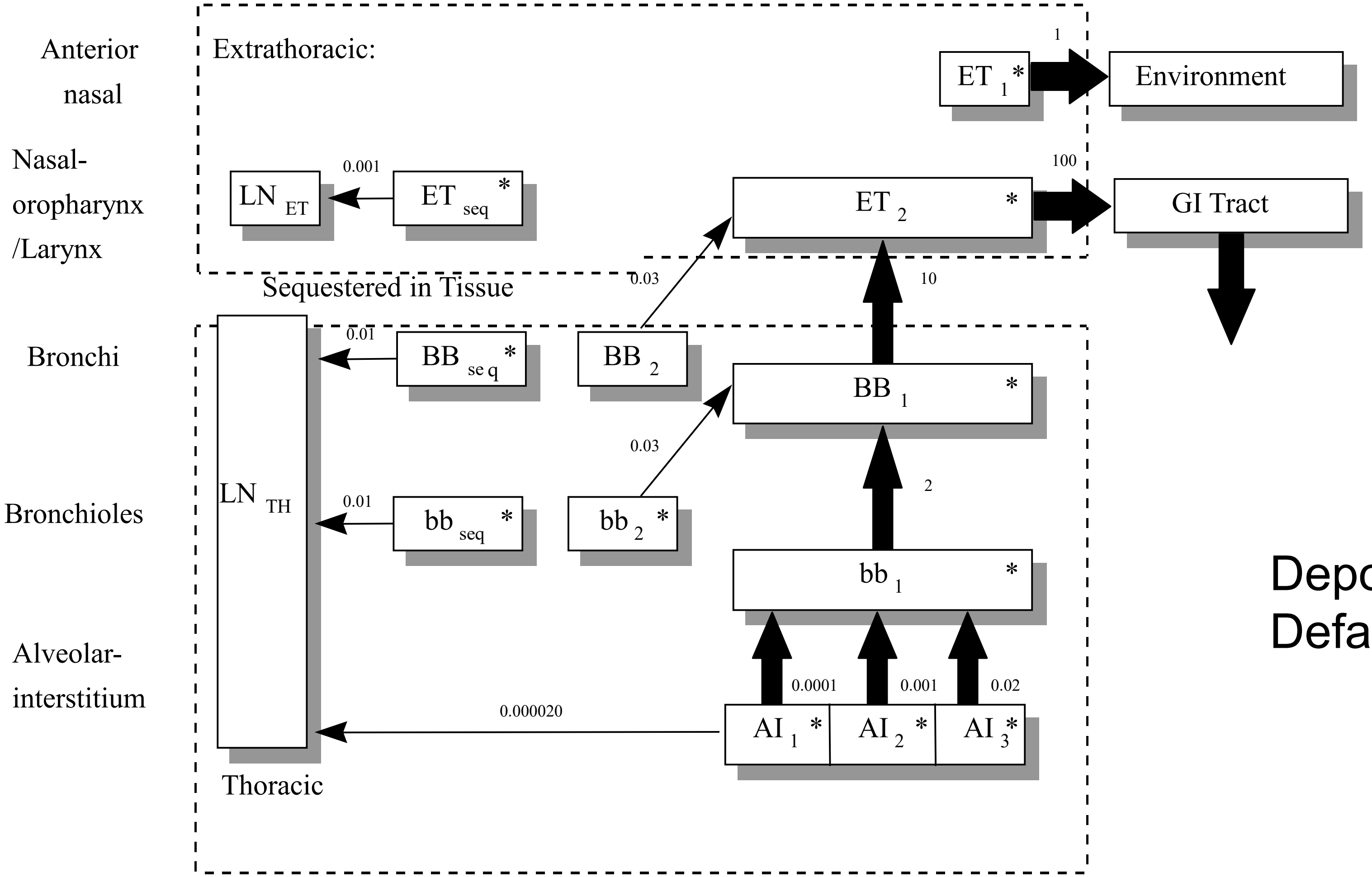


The model is intended for use with aerosol distributions with AMADs between 0.2 and 10 μm and with geometric standard deviations of less than 4.5.

Respiratory Tract Regions Defined in the ICRP Publication 66 Model (1994)

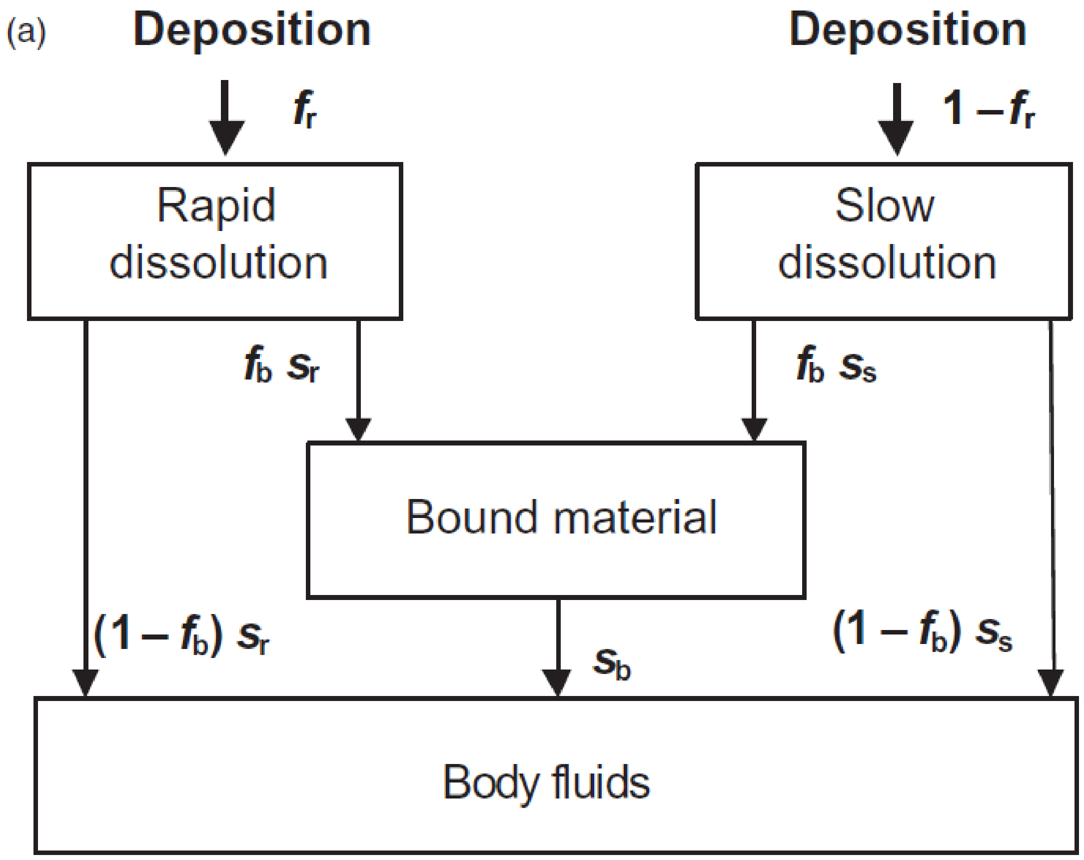


The ICRP Publication 66 Human Respiratory Tract Model - HRTM (1994)



Deposition of particles:
Default: AMAD = 5 μm

The ICRP Publication 66 HRTM
- Blood Absorption -



Type		F (fast)	M (moderate)	S (slow)
Model parameters				
Fraction dissolved rapidly	f_r	1	0.1	0.001
Approximate dissolution rates				
Rapid (d^{-1})	s_r	100	100	100
Slow (d^{-1})	s_s	–	0.005	0.0001
Fraction to bound state	f_b	0	0	0
Uptake rate from bound state (d^{-1})	s_b	–	–	–

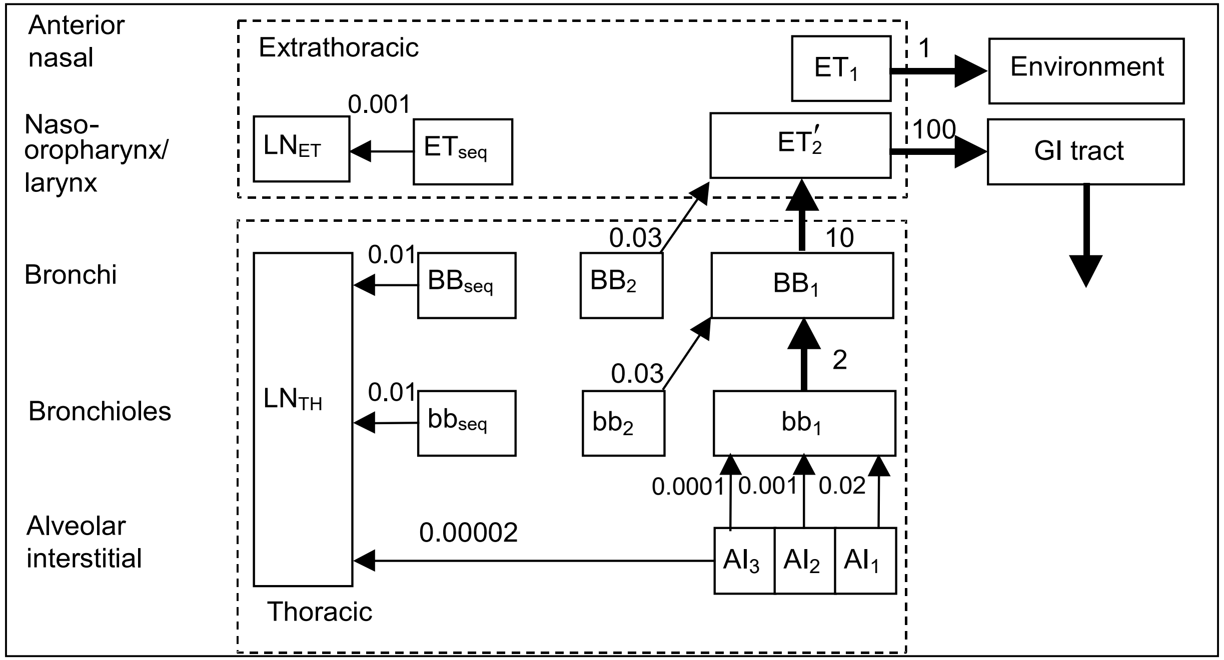
Table 15.2. Absorption parameter values for inhaled and ingested uranium.

Inhaled particulate materials		Absorption parameter values* f_r	s_r (d^{-1})	s_s (d^{-1})	Absorption from the alimentary tract, f_A §
Specific parameter values†					
Intermediate Type F/M: uranyl nitrate $UO_2(NO_3)_2$; uranium peroxide hydrate UO_4; ammonium diuranate ADU; uranium trioxide UO_3		0.8	1	0.01	0.016
Intermediate Type M/S: uranium octoxide U_3O_8; uranium dioxide UO_2		0.03	1	5×10^{-4}	6×10^{-4}
Uranium aluminide UAl_X		‡	‡	‡	0.002
Default parameter values§,¶					
Absorption type	Assigned forms				
F	Uranium hexafluoride, UF_6; uranyl tri-butyl-phosphate	1	10	–	0.02
M**	Uranyl acetylacetonate; UF_4; depleted uranium aerosols from use of kinetic energy penetrators; vaporised U metal, UF_4	0.2	3	0.005	0.004
S	—	0.01	3	1×10^{-4}	2×10^{-4}
Ingested materials††					
Soluble forms (Type F)		–	–	–	0.02
Relatively insoluble forms (as assigned to Types M and S for inhalation)		–	–	–	0.002

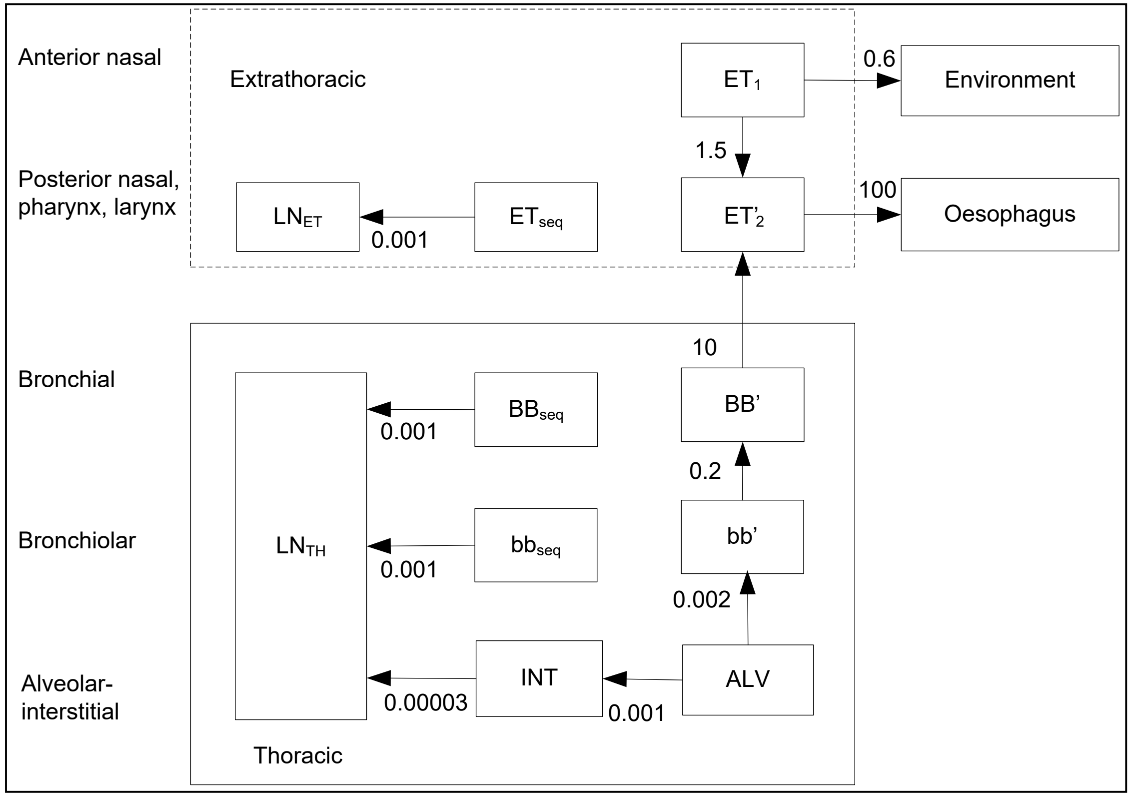
Table 22.11. Absorption parameter values for inhaled and ingested plutonium.

Inhaled particulate materials		Absorption parameter values* f_r	s_r (d^{-1})	s_s (d^{-1})	Absorption from the alimentary tract, f_A**
Specific parameter values†					
Plutonium nitrate, $Pu(NO_3)_4$		0.2	0.4	0.002	1×10^{-4}
^{239}Pu dioxide‡, $^{239}PuO_2$; plutonium in mixed oxide [$(UO_2 + PuO_2)$ or $(U,Pu)O_2$]		0.004	0.4	1×10^{-5}	2×10^{-6}
^{238}Pu dioxide, $^{238}PuO_2$ ceramic		§	§	§	5×10^{-8}
^{238}Pu dioxide, $^{238}PuO_2$ non-ceramic		¶	¶	¶	1×10^{-5}
Plutonium dioxide 1-nm nanoparticles, 1-nm PuO_2		0.7	0.4	0.005	3.5×10^{-4}
Default parameter values**,††					
Absorption type	Assigned forms				
F	—	1	0.4	—	5×10^{-4}
M‡‡	Plutonium citrate; plutonium tri-butyl-phosphate (Pu-TBP); plutonium chloride ($PuCl_3$)	0.2	0.4	0.005	1×10^{-4}
S	—	0.01	0.4	1×10^{-4}	5×10^{-6}
Ingested materials§§					
Soluble forms (nitrate, chloride, bicarbonates)					5×10^{-4}
Insoluble forms (oxides)					1×10^{-5}
All other unidentified chemical forms					5×10^{-4}

HRTM



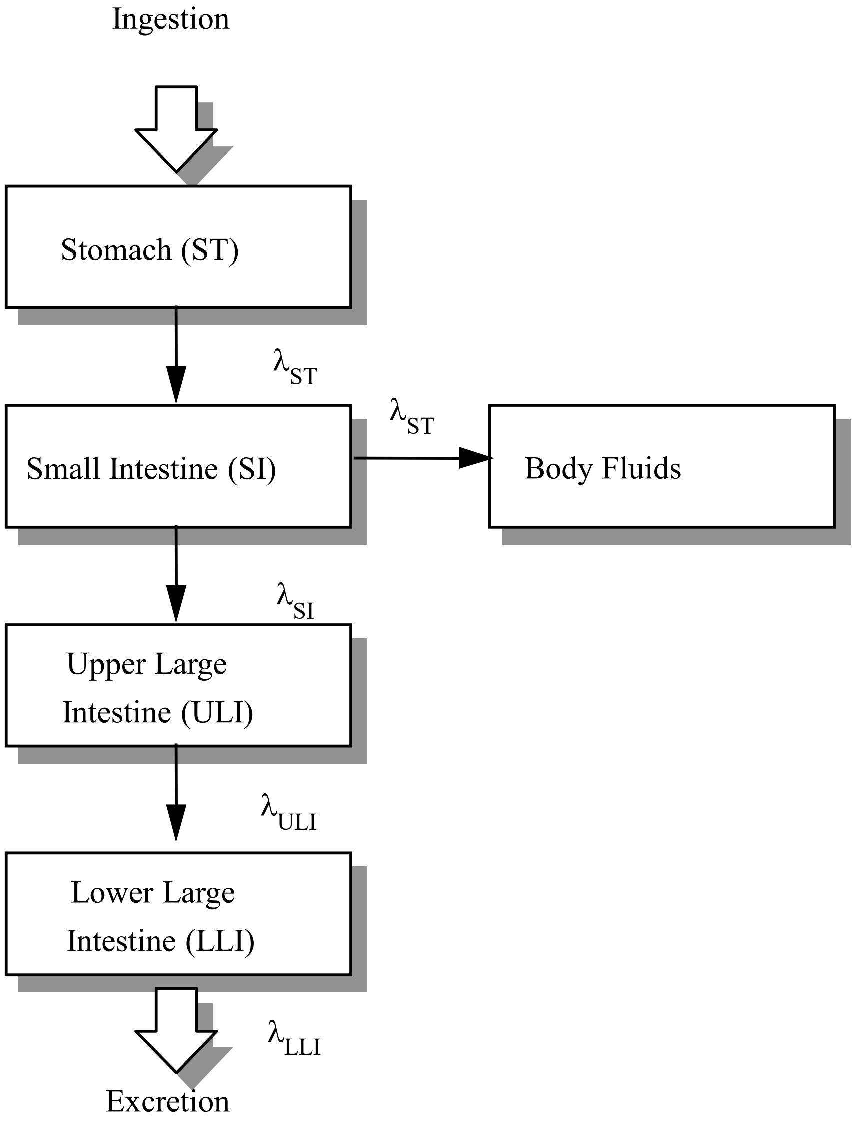
Former model: ICRP-66 (1994)



Adopted model: ICRP-130 (2013)

Evolution of the Gastrointestinal Tract Models

The ICRP Publication 30 Gastrointestinal Tract Model (1979)



Section of GI tract	Mass of Contents (g)	Mean residence time (d)	λ (d^{-1})
ST	250	1/24	24
SI	400	4/24	6
ULI	220	13/24	1.8
LLI	135	24/24	1

Health Physics Pergamon Press 1966. Vol. 12, pp. 131—161. Printed in Northern Ireland

A REVIEW OF THE PHYSIOLOGY OF THE GASTRO-INTESTINAL TRACT IN RELATION TO RADIATION DOSES FROM RADIOACTIVE MATERIALS*

I. S. EVE.

United Kingdom Atomic Energy Authority, Health and Safety Branch, Radiological Protection Division, Harwell, Berkshire, England

(*Received* 16 *July* 1965)

Abstract—The following table is proposed for the GI-tract of Standard Man.

Portion of GI tract	Mass of contents (g)	Time food remains (days)
Stomach	250	1/24
Small intestine	400	4/24
Upper large intestine	220	13/24
Lower large intestine	135	24/24

For some methods of calculation, the fraction of the 24 hr during which a section of the GI-

Example: Biokinetic Model for the GI-Tract Formal Description

$$\frac{d}{dt} q_{ST}(t) = -\lambda_{ST} q_{ST}(t) - \lambda_R q_{ST}(t) + \dot{I}(t)$$

$$\frac{d}{dt} q_{SI}(t) = -\lambda_{SI} q_{SI}(t) - \lambda_R q_{SI}(t) - \lambda_B q_{SI}(t) + \lambda_{ST} q_{ST}(t)$$

$$\frac{d}{dt} q_{ULI}(t) = -\lambda_{ULI} q_{ULI}(t) - \lambda_R q_{ULI}(t) + \lambda_{SI} q_{SI}(t)$$

$$\frac{d}{dt} q_{LLI}(t) = -\lambda_{LLI} q_{LLI}(t) - \lambda_R q_{LLI}(t) + \lambda_{ULI} q_{ULI}(t)$$

$$\frac{\lambda_B}{\lambda_{SI} + \lambda_B} = f_1 \quad \therefore \quad \frac{f_1 \lambda_{SI}}{1 - f_1} = \lambda_B$$

where λ_R is the radioactive decay constant of the radionuclide in question;

$\lambda_B q_{SI}(t)$ is the rate of transfer of activity to body fluids from the small intestine, assumed to be the only site of absorption from the GI tract to body fluids, and

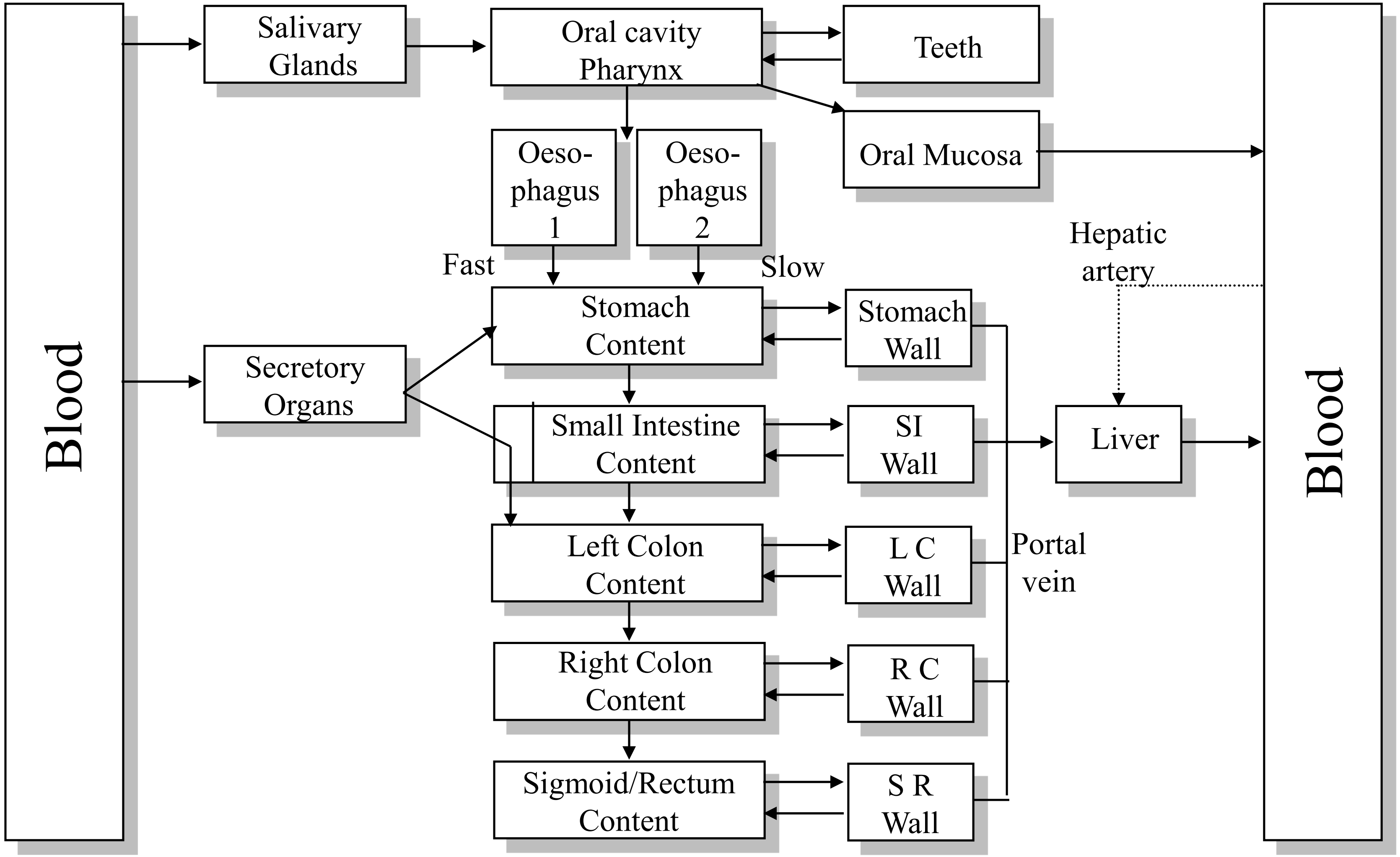
$\dot{I}(t)$ is the rate of ingestion of activity of the radionuclide at time t.

The Need for a New GI Tract Model

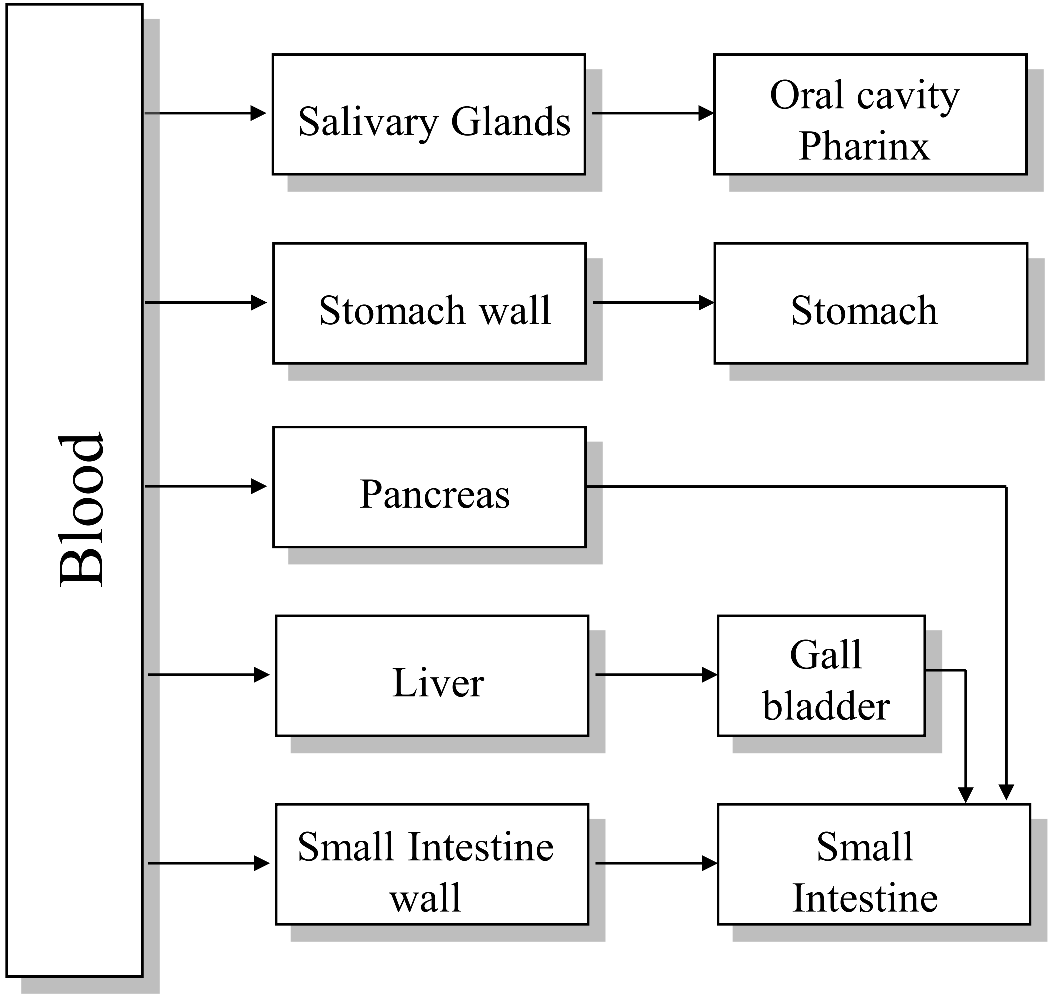
Since ICRP-30 (1979):

- Specific risk estimates for cancer of the stem cells in stratified squamous epithelium, as in the lining of the mouth, the tongue, esophagus, stomach and colon have been included.
- More data available on the transit of materials through the different regions of the gut.

The ICRP Human Alimentary Tract Model – HATM (2006)



Routes of Secretion Into the Alimentary Tract



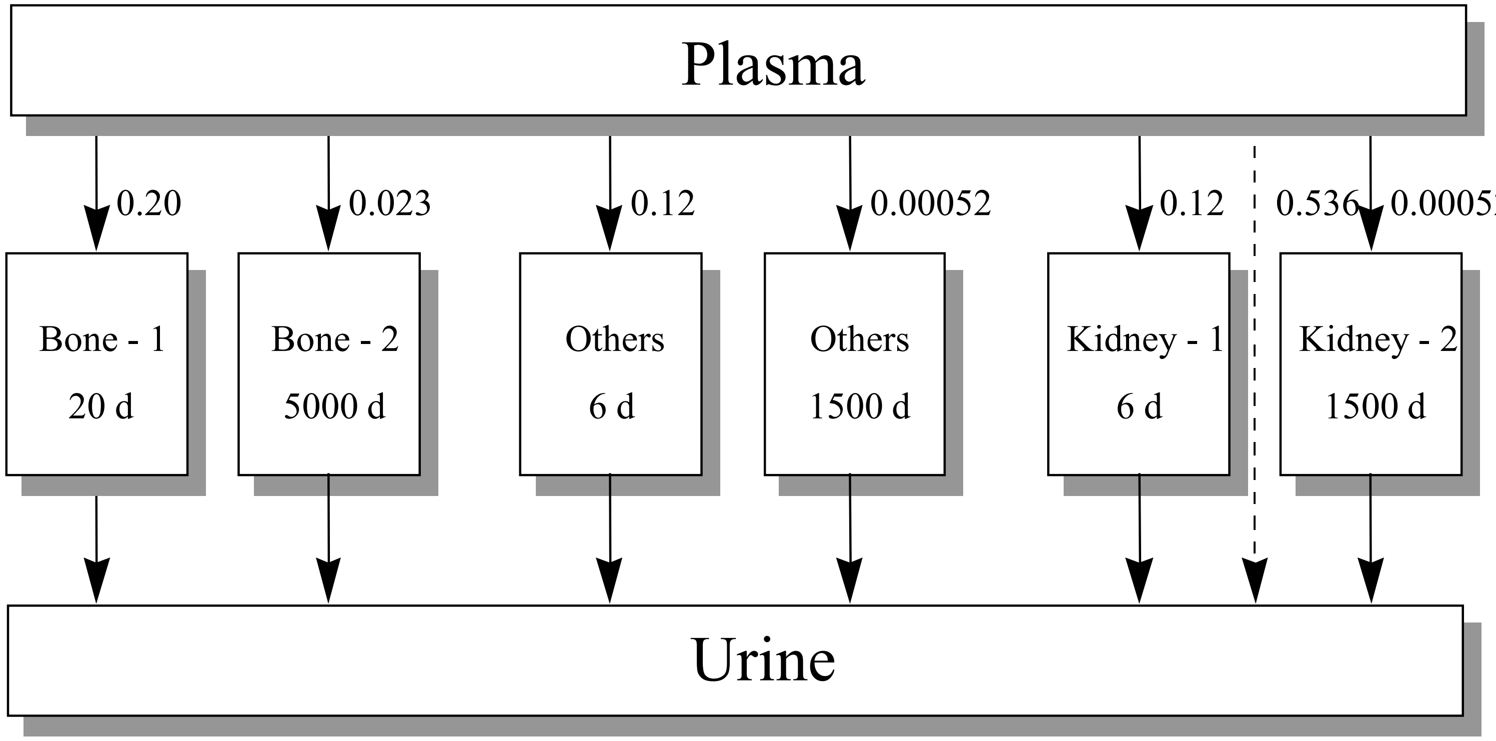
Transfer Coefficients (per day) for the movement of alimentary tract between regions

Source	-> Target	Infant	1-yr_old	5-yr_old	10-yr_old	15-yr_old	Adult male	Adult female
O-cavity	->Oesophag-f	3.8880E+04	6.4800E+03	6.4800E+03	6.4800E+03	6.4800E+03	6.4800E+03	6.4800E+03
O-cavity	->Oesophag-s	4.3200E+03	7.2000E+02	7.2000E+02	7.2000E+02	7.2000E+02	7.2000E+02	7.2000E+02
Oesophag-f	->St-cont	2.1600E+04	1.2343E+04	1.2343E+04	1.2343E+04	1.2343E+04	1.2343E+04	1.2343E+04
Oesophag-s	->St-cont	2.8800E+03	2.1600E+03	2.1600E+03	2.1600E+03	2.1600E+03	2.1600E+03	2.1600E+03
St-cont	->SI-cont	1.9200E+01	2.0570E+01	2.0570E+01	2.0570E+01	2.0570E+01	2.0570E+01	1.5160E+01
SI-cont	->RC-cont	6.0000E+00	6.0000E+00	6.0000E+00	6.0000E+00	6.0000E+00	6.0000E+00	6.0000E+00
RC-cont	->LC-cont	3.0000E+00	2.4000E+00	2.1820E+00	2.1820E+00	2.1820E+00	2.0000E+00	1.5000E+00
LC-cont	->RS-cont	3.0000E+00	2.4000E+00	2.1820E+00	2.1820E+00	2.1820E+00	2.0000E+00	1.5000E+00
RS-cont	->Feces	2.0000E+00	2.0000E+00	2.0000E+00	2.0000E+00	2.0000E+00	2.0000E+00	1.5000E+00
O-cavity	->Teeth-S	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
Teeth-S	->O-cavity	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
O-cavity	->O-mucosa	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
O-mucosa	->O-cavity	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
O-mucosa	->Blood	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
St-cont	->St-wall	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
St-wall	->St-cont	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
St-wall	->Blood	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
SI-cont	->SI-wall	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

……………………………………………………..

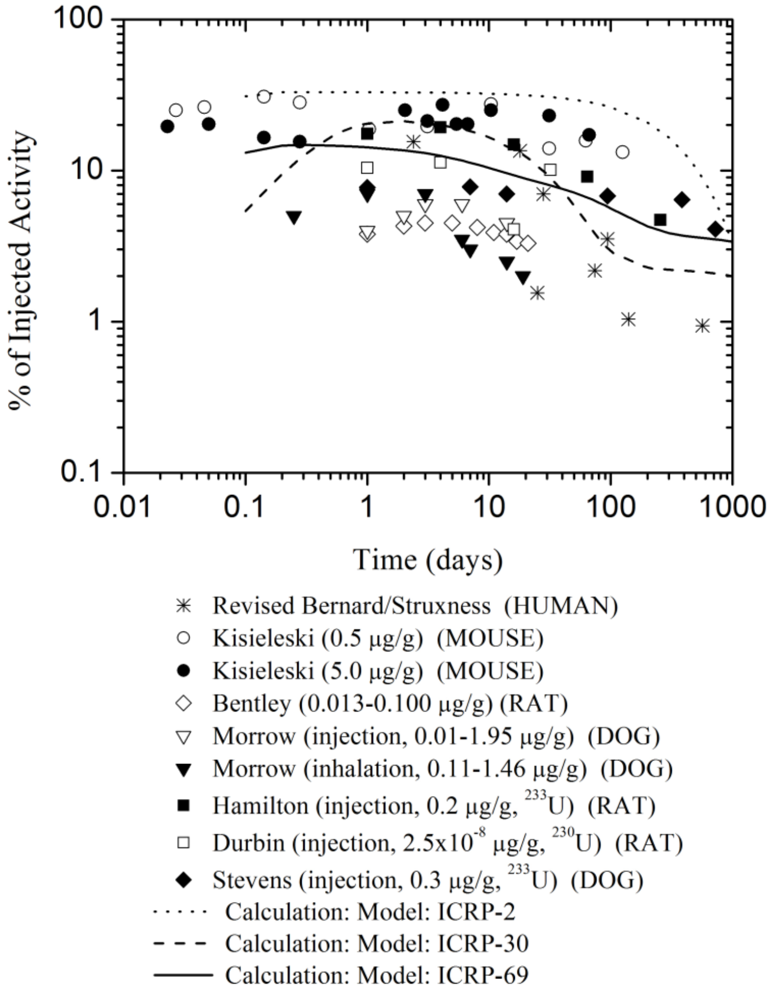
Evolution of the Systemic Models

The ICRP Publication 30 Uranium Systemic Model (1979)

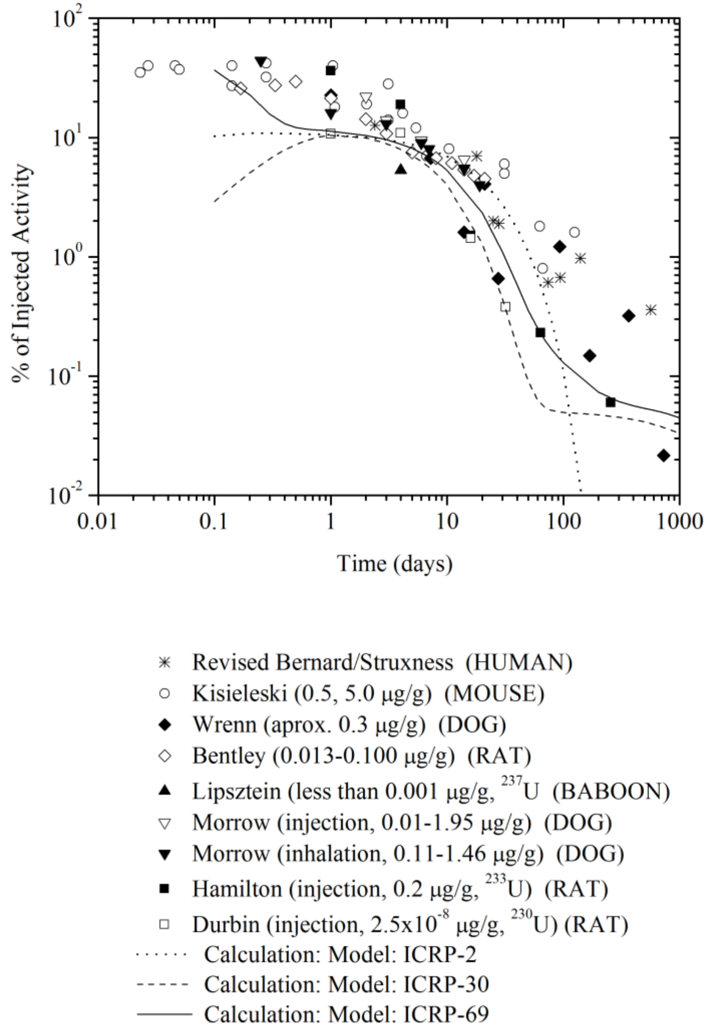


Organ Content (%) After a Single Injection of Soluble Uranium

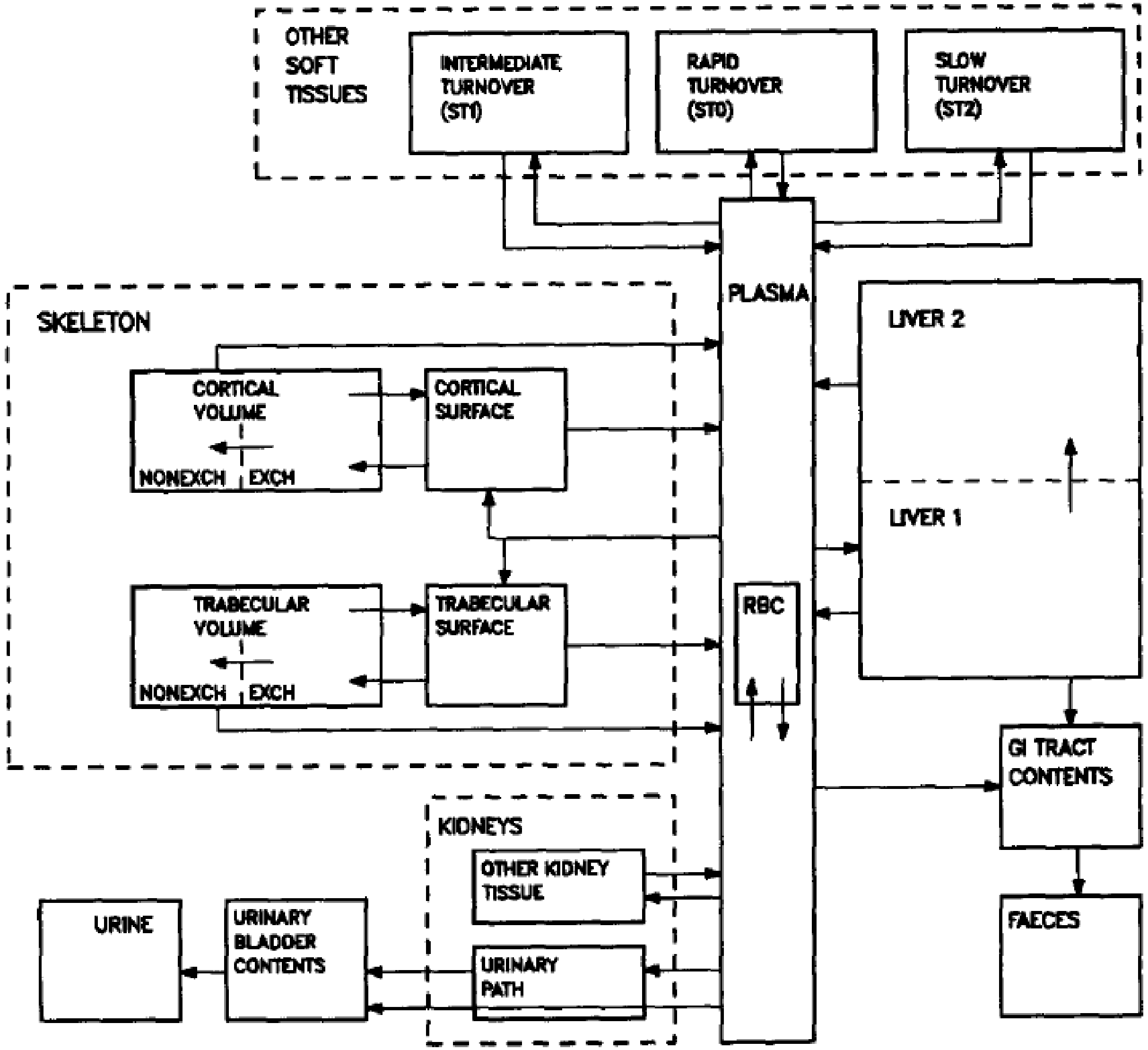
Skeleton



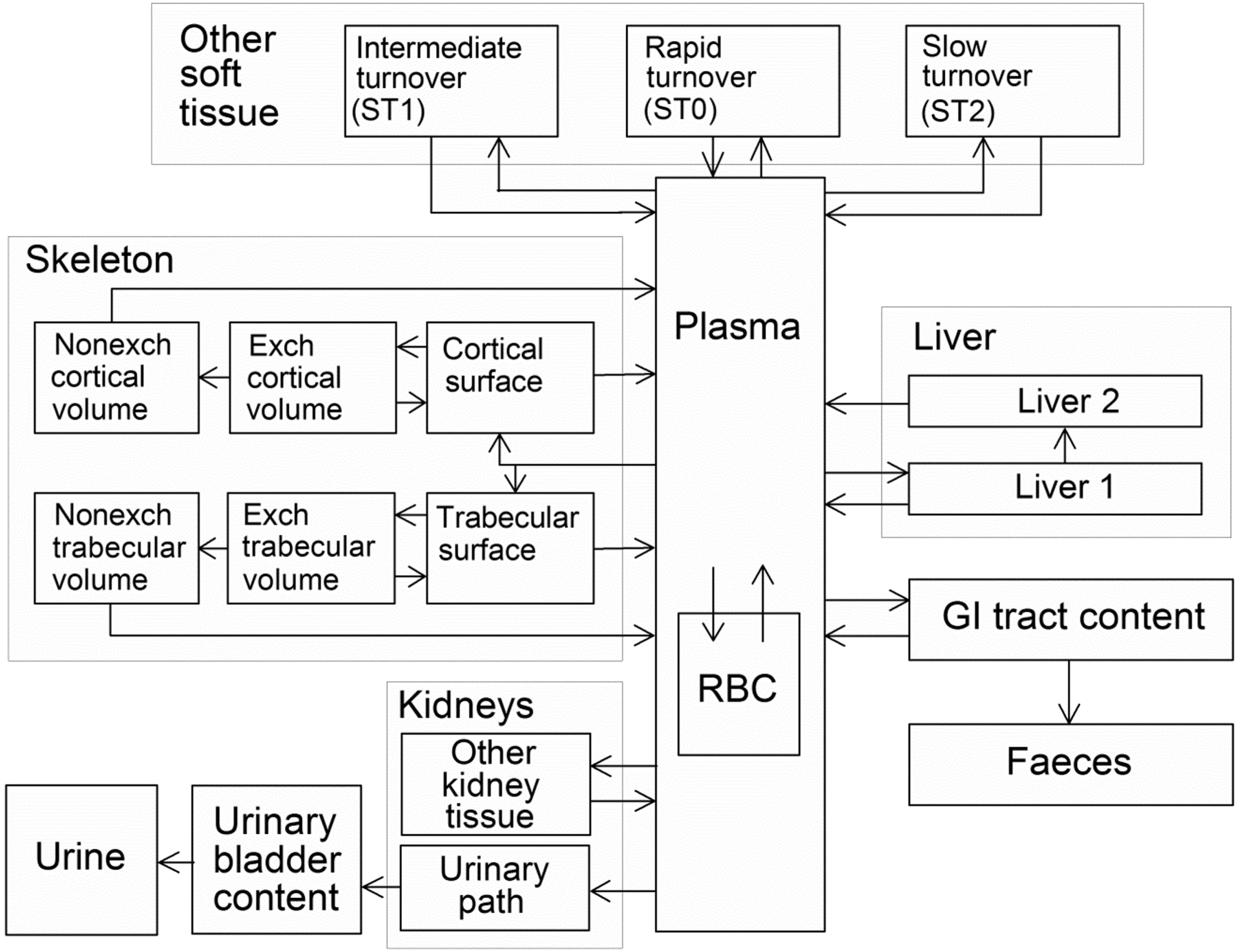
Kidneys



The ICRP Publication 69 Systemic Model for Uranium (1994)



The ICRP Publication 137 Systemic Model for Uranium (2017)



Distribution and Excretion of Plutonium Administered Intravenously to Man (1980)

WRIGHT H. LANGHAM *et al.*

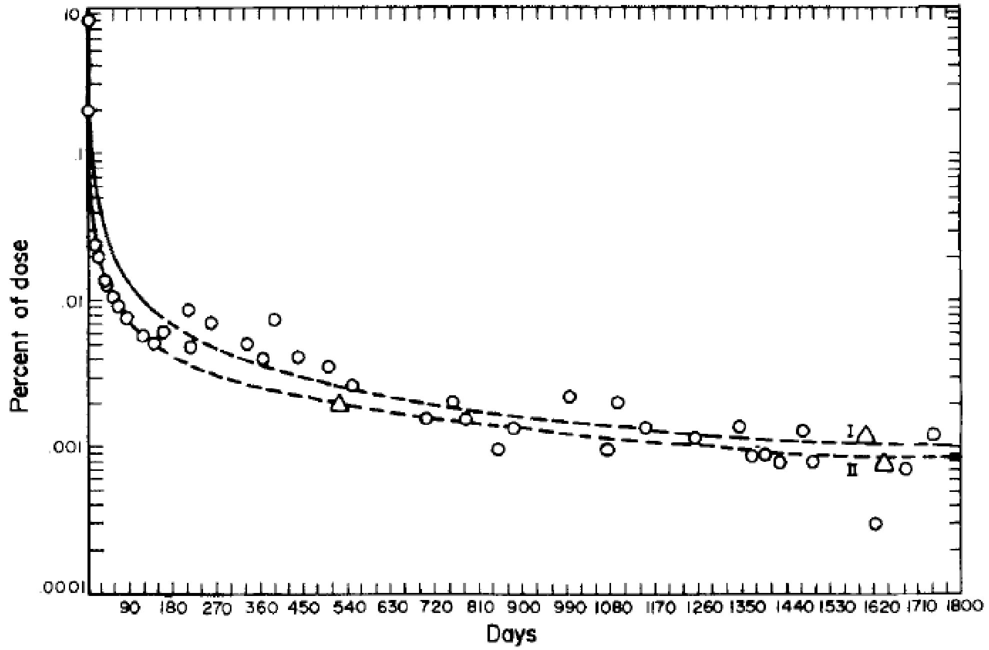
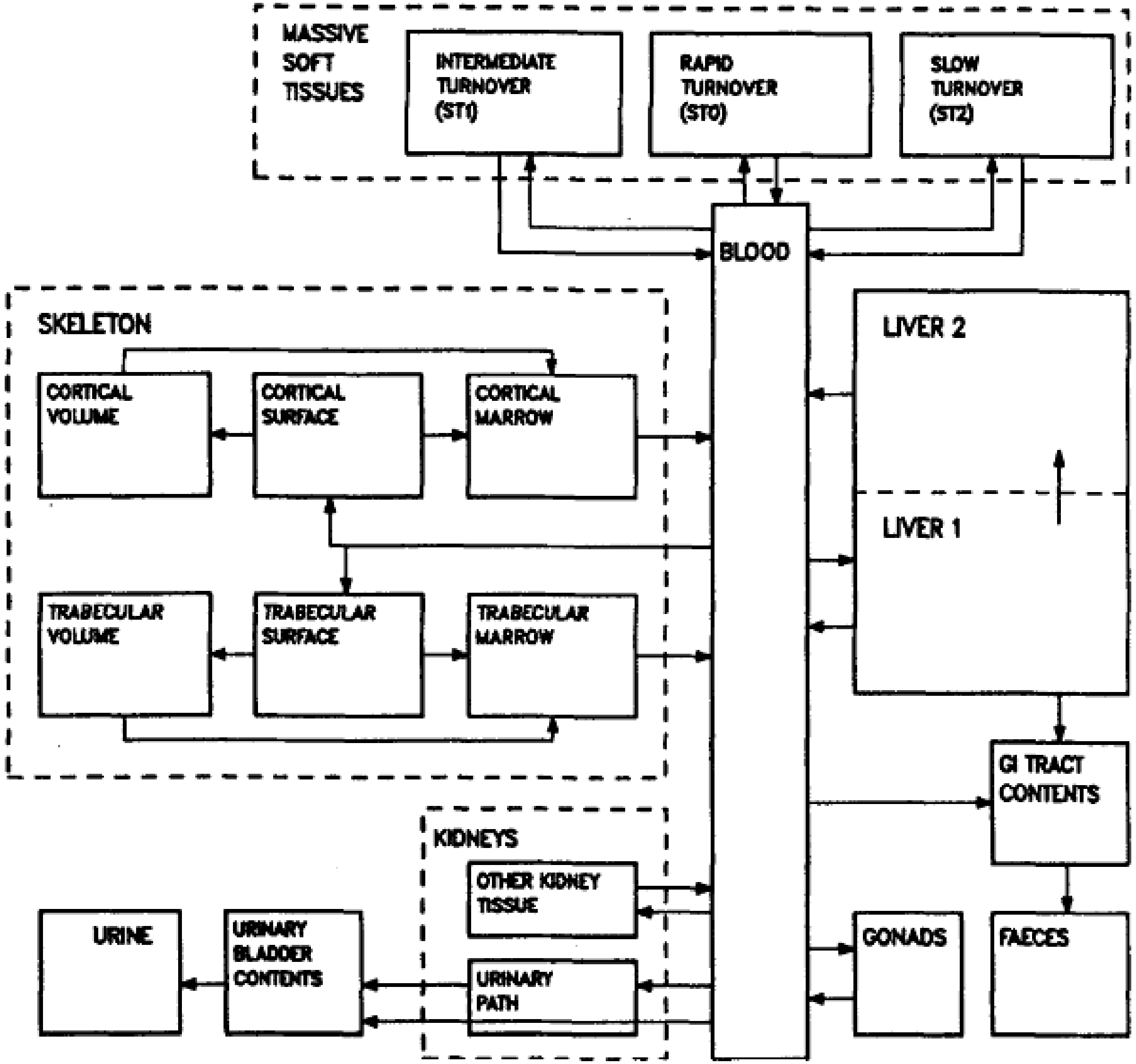


FIG. 5. Adjusted urinary and fecal excretion curves through 1750 days.
I. Fecal plus urinary excretion $Y_{ua} + f = 0.20\,X^{-0.74} + 0.63\,X^{-1.09}$.
II. Urinary excretion $Y_{ua} = 0.20\,X^{-0.74}$.
—Portion of curve based on experimental observations through 138 days.
--Adjusted portion of curve through 1750 days.
○Points established from urinary excretion values for Los Alamos Laboratory personnel.
△Average of four consecutive daily values from a single experimental case.

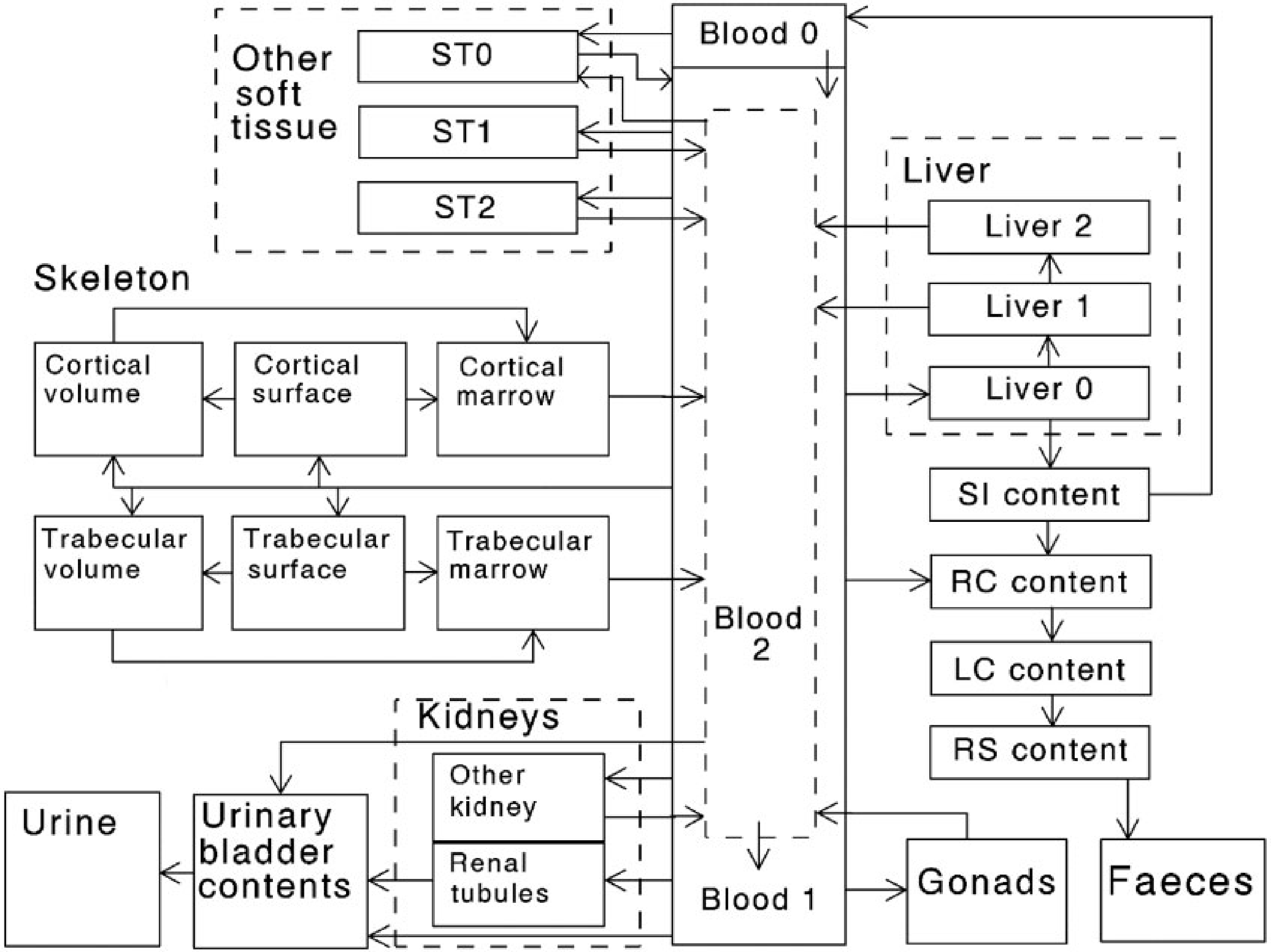
Plutonium Biokinetic Model Proposed by ICRP-2 (1959)

Organ	Fraction from blood	Biological half-life, days	
Bone	0.8	7.3×10^4	(200 y)
Liver	0.15	3.0×10^4	(82 y)
Kidneys	0.02	3.2×10^4	(87 y)

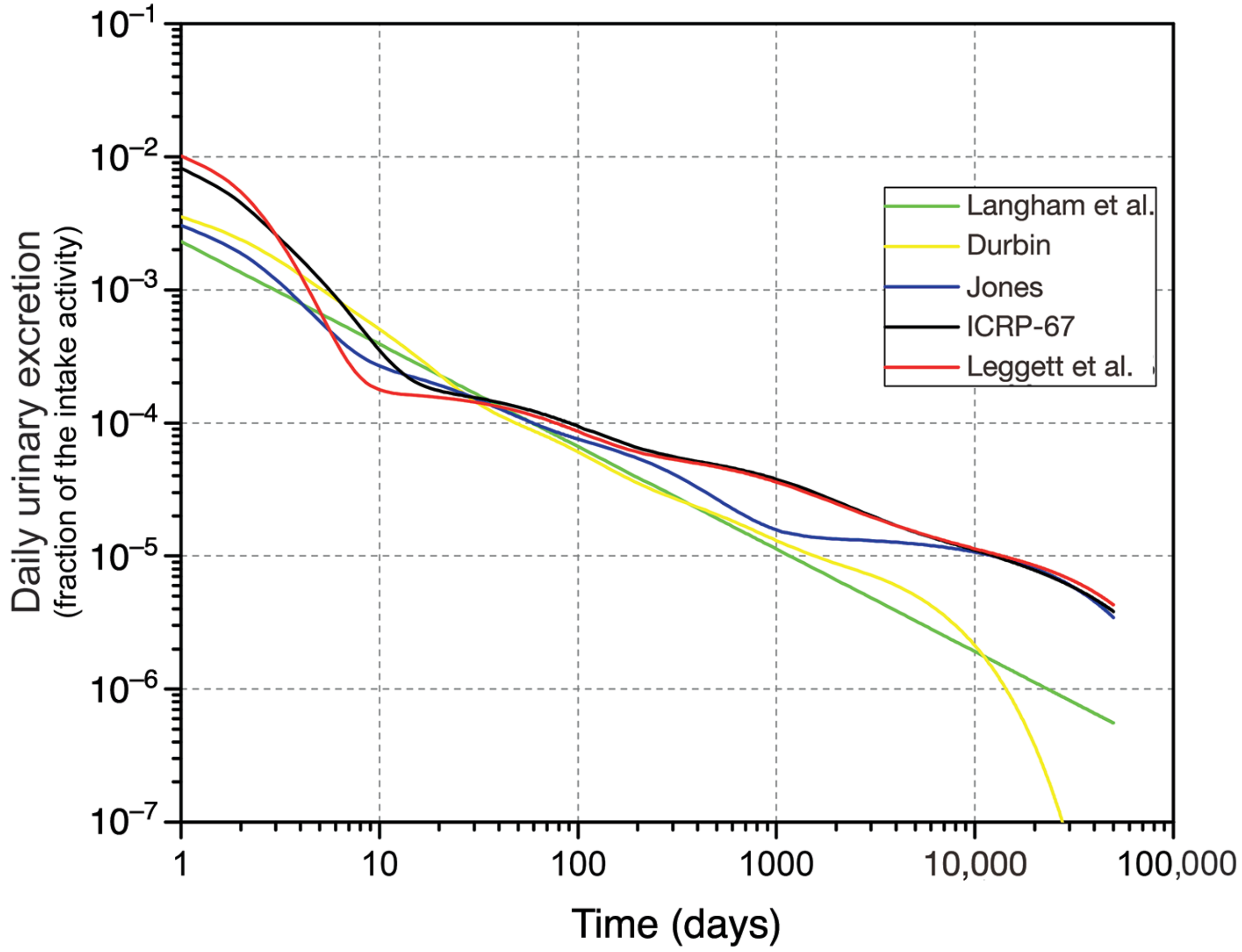
Diagram of the Biokinetic Model for Plutonium (ICRP Publication 67, 1994)



Systemic model structure for plutonium, and connections to compartments of the HATM (ICRP-141)



Predictions of daily urinary excretion fractions using the models of Langham et al., Durbin, Jones, ICRP-67, and Leggett et al.



Transfer Rates of the ICRP-141 Plutonium Systemic Model for Adult (d^{-1})

Blood	->Other_3	3.0000E+02	Kidneys_1	->UB-cont	1.7329E-02
Blood	->Blood_5	7.0000E+02	Kidneys_2	->Blood_4	1.2660E-04
Blood_5	->Liver_1	4.6200E-01	Other_4	->Blood_4	1.3860E-03
Blood_5	->C-bone-S	8.7780E-02	Other_5	->Blood_4	1.2660E-04
Blood_5	->C-bone-V	4.6200E-03	Liver_1	->SI-cont	9.2420E-04
Blood_5	->T-bone-S	1.2474E-01	Liver_1	->Liver_2	4.5286E-02
Blood_5	->T-bone-V	1.3860E-02	Liver_2	->Blood_4	1.5200E-03
Blood_5	->UB-cont	1.5400E-02	Liver_2	->Liver_3	3.8000E-04
Blood_5	->Kidneys_1	7.7000E-03	Liver_3	->Blood_4	1.2660E-04
Blood_5	->Kidneys_2	3.8500E-04	Testes	->Blood_4	3.8000E-04
Blood_5	->RC-cont	1.1550E-02	Ovaries	->Blood_4	3.8000E-04
Blood_5	->Testes	2.6950E-04	C-bone-S	->C-marrow	8.2100E-05
Blood_5	->Ovaries	8.4700E-05	C-bone-S	->C-bone-V	2.0500E-05
Blood_5	->Other_4	1.8511E-02	C-bone-V	->C-marrow	8.2100E-05
Blood_5	->Other_5	2.3100E-02	T-bone-S	->T-marrow	4.9300E-04
Other_3	->Blood_5	9.9000E-02	T-bone-S	->T-bone-V	1.2300E-04
Blood_4	->UB-cont	3.5000E+00	T-bone-V	->T-marrow	4.9300E-04
Blood_4	->Blood_5	6.7550E+01	C-marrow	->Blood_4	7.6000E-03
Blood_4	->Other_3	2.8950E+01	T-marrow	->Blood_4	7.6000E-03

Example of input matrix for the system of differential equations solver

	O-cavity_1	Oesophag-f	Oesophag-s	St-cont_1	SI-cont_1	RC-cont_1	LC-cont_1	RS-cont_1	Feces	Blood_1	Urine	Blood_2	Blood_3	Blood_4	Blood_5	Blood_6	C-bone-S	C-b
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
1	-7.20E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
2	6.48E+03	-1.23E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
3	7.20E+02	0.00E+00	-2.16E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
4	0.00E+00	1.23E+04	2.16E+03	-2.06E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
5	0.00E+00	0.00E+00	0.00E+00	2.06E+01	-6.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.00E+00	-2.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.00E+00	-2.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
8	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.00E+00	-2.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
9	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.00E+00	-1.32E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.00E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.00E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.32E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.32E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.32E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.32E-04	0.00E+00	0.00E+00	0.00E+00	0.0
15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.00E+02	0.00E+00	0.00E+00	0.0
16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.76E+01	-7.70E-01	0.00E+00	0.0
17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.78E-02	-2.35E-04	0.0
18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.62E-03	2.05E-05	-2.
19	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
20	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0
21	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.21E-05	8.

Examples of Solvers

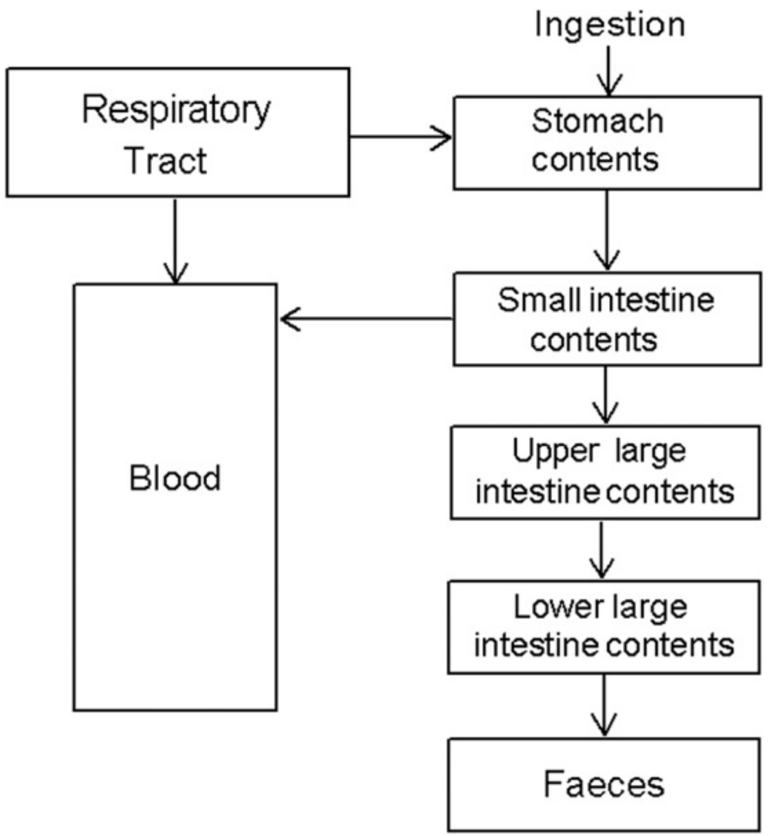
- Analytical solver: EISPACK

  (*EISPACK*, a FORTRAN77 library which calculates the eigenvalues and eigenvectors of a matrix.)

- Numerical solver: DLSODES

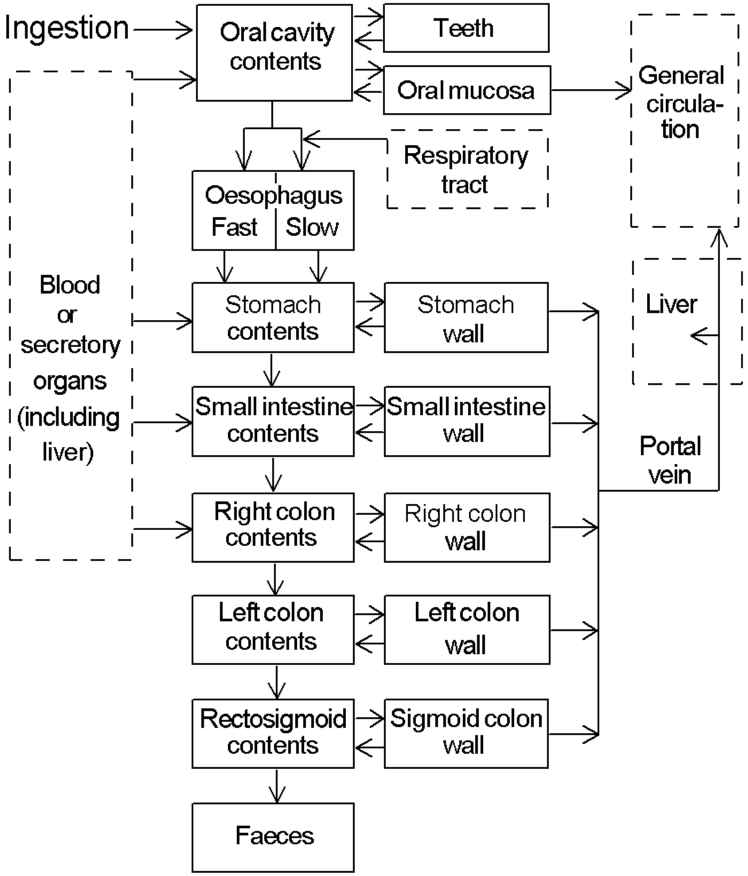
  (LSODE (Livermore Solver for Ordinary Differential Equations) solves stiff and nonstiff systems of the form dy/dt = f(t,y))

Biokinetic Models:
Alimentary Tract



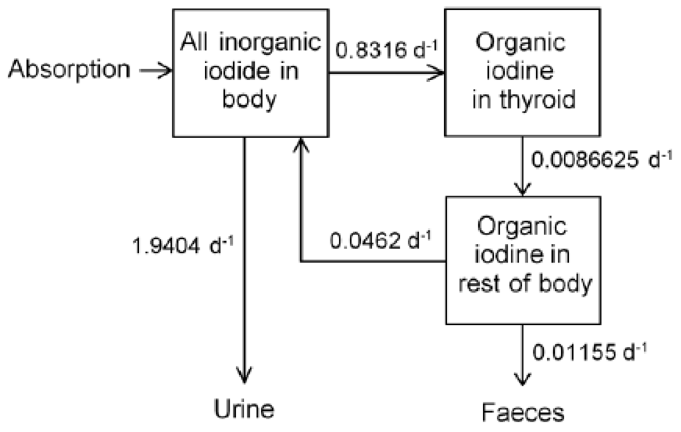
Former model (ICRP 1979)

→



Adopted model (2005)

Biokinetic Models:
Systemic model for Iodine



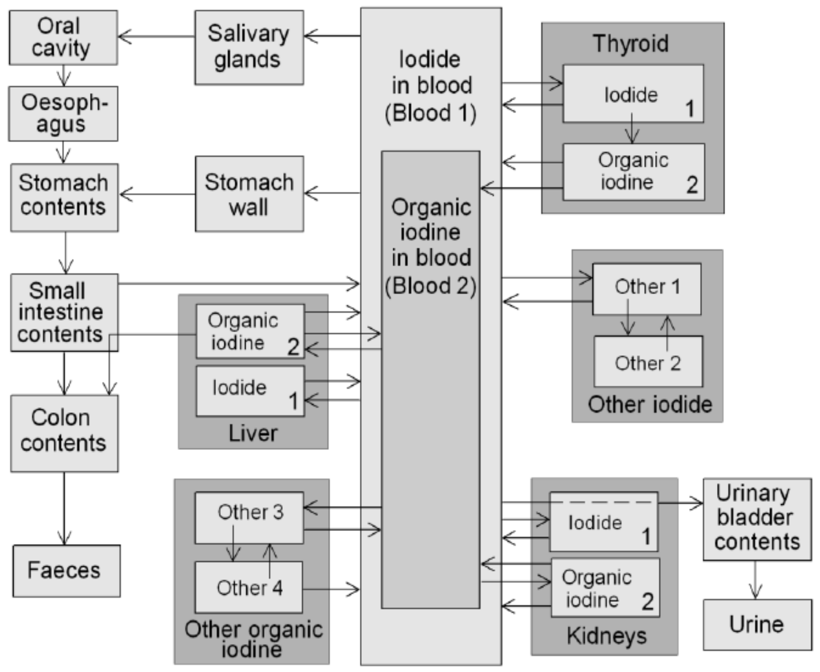
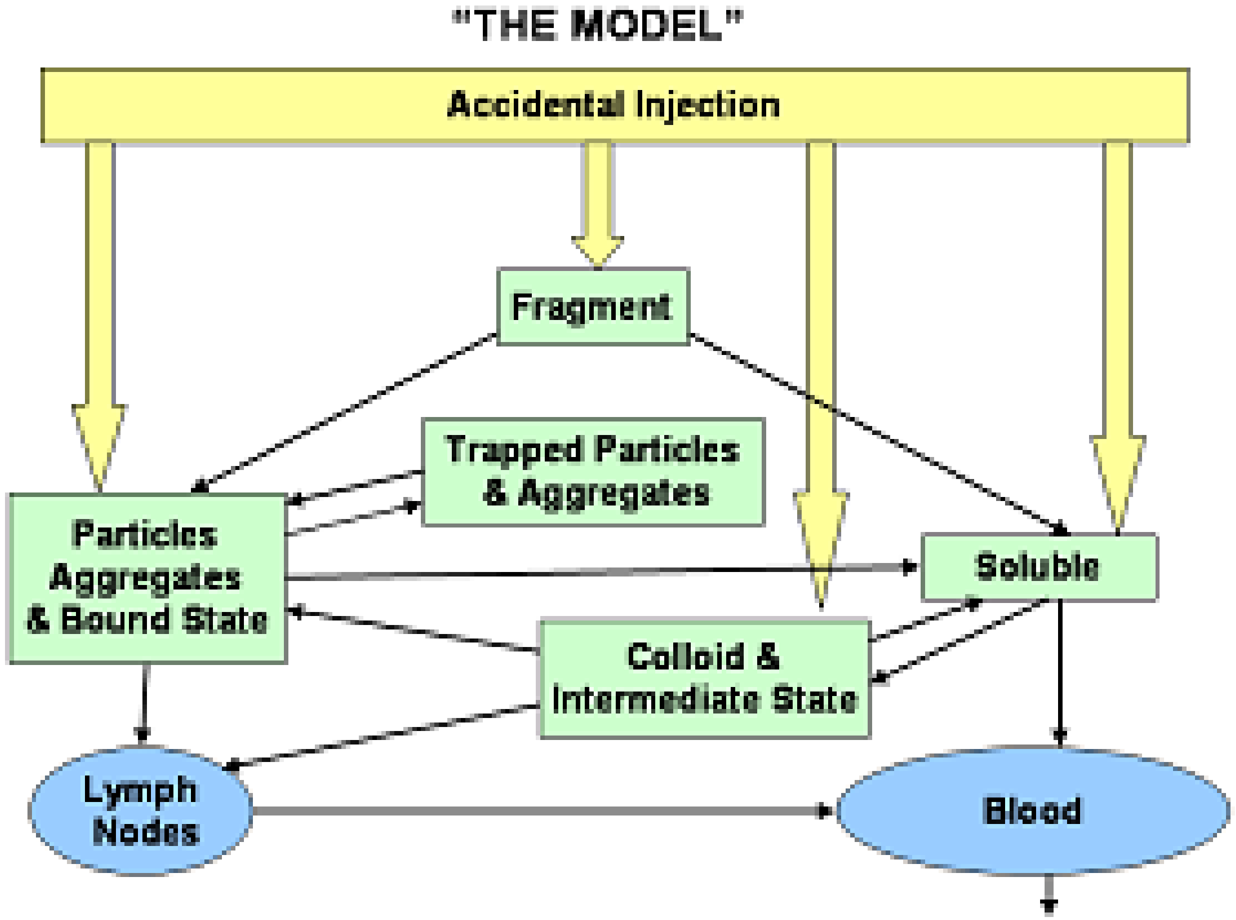


Figure 5-2. Structure of the biokinetic model for systemic iodine used in this report.

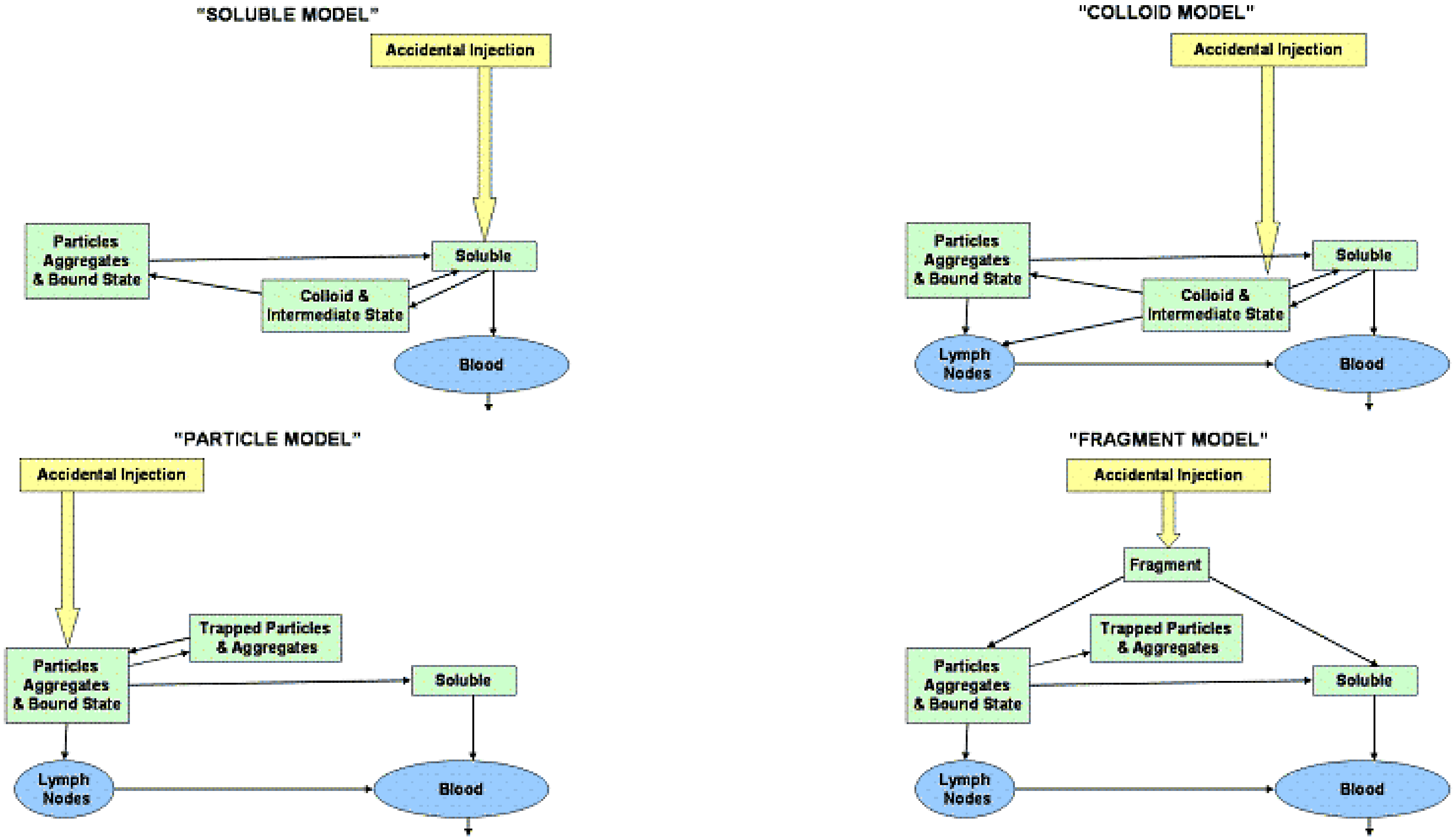
Former model (ICRP 1994)

Adopted model (2013)

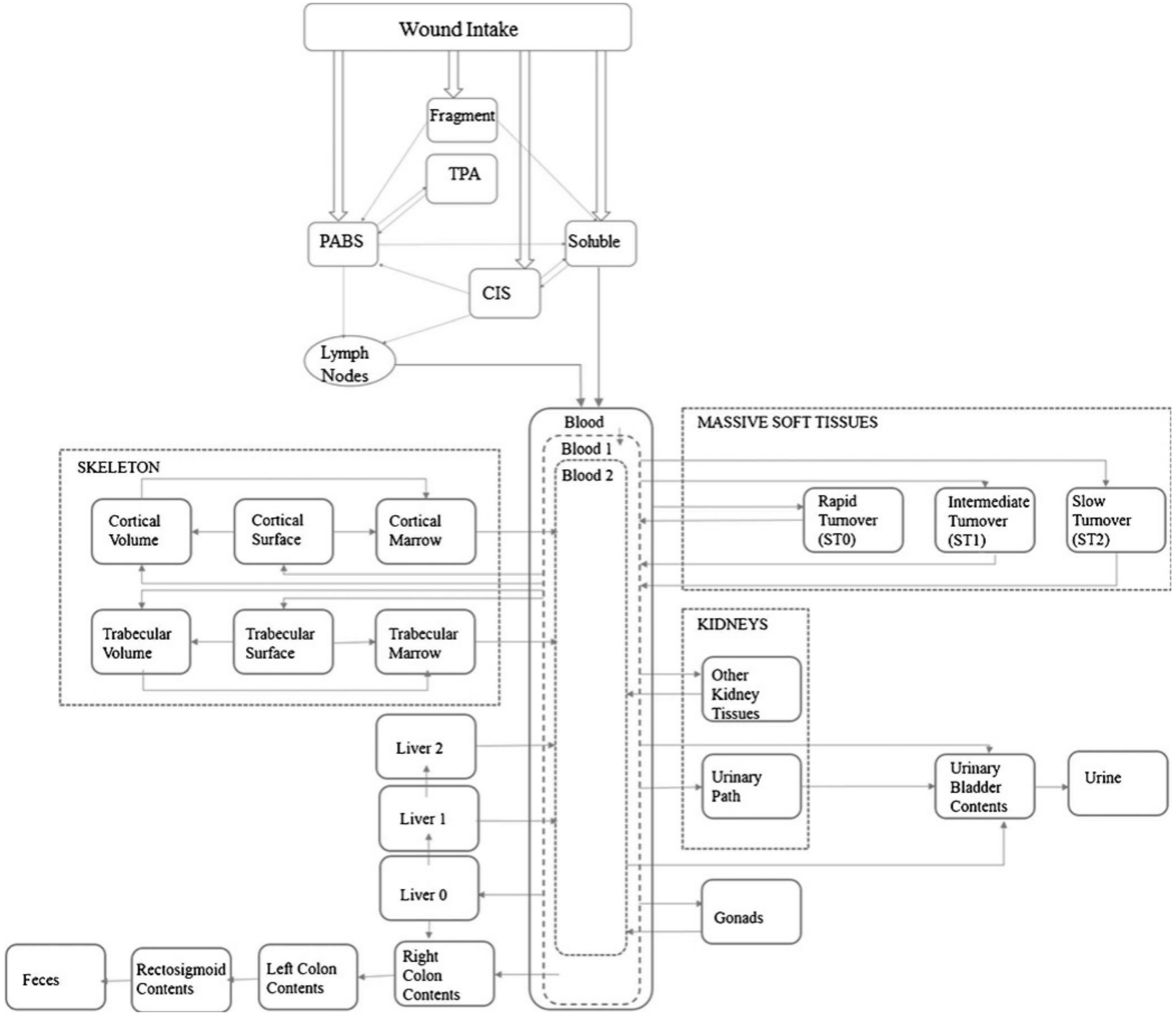
Wound Model (NCRP 2005)



Wound Model Categories



Coupling the Wound Model with the Pu Systemic Model



Dosimetric Models and Their Evolution

Dosimetric Models (Anatomical Model)

Mathematical description of Reference Man is used to compute the energy deposition in organs/tissues of the body from photon, electron and neutron radiations.

Phantom used in Monte Carlo simulations of the transport of radiation. Source may be within the body or outside the body.

Model has been extended to age groups other than adults.

The ORNL Adult Male Phantom
(Geometric Model - 1974)

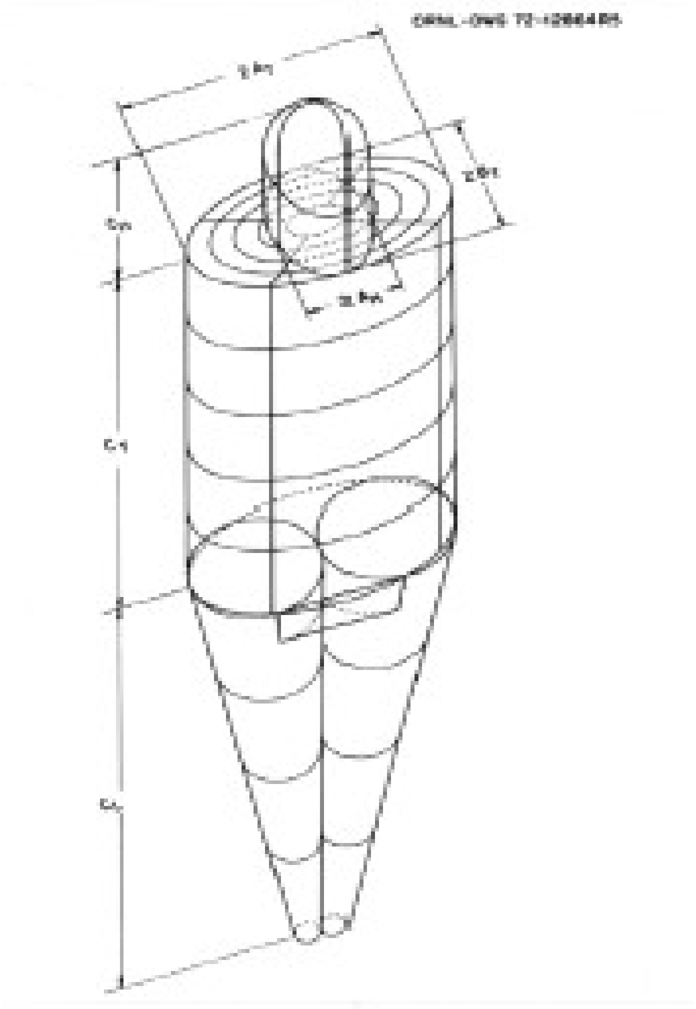


Fig. A-l. The "Adult male" phantom. Breasts are not shown.

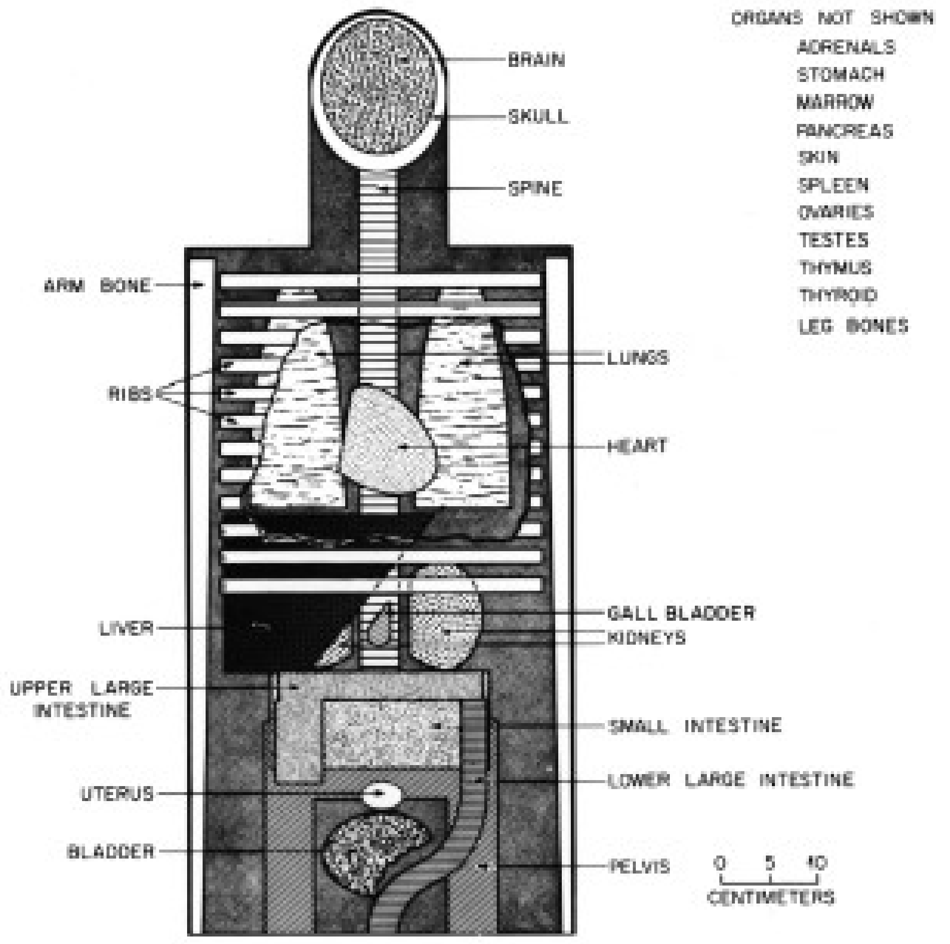
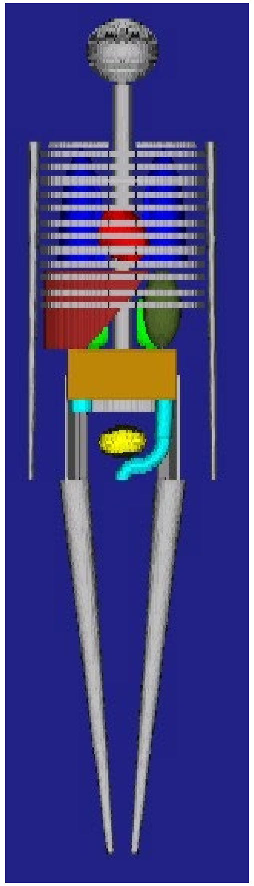


Fig. A-3. Anterior view of the principal organs in the head and trunk of the adult phantom developed by Snyder et al. (1974). Although the heart and head have been modified in this report, this schematic illustrates the simplicity of the geometries of the organs.

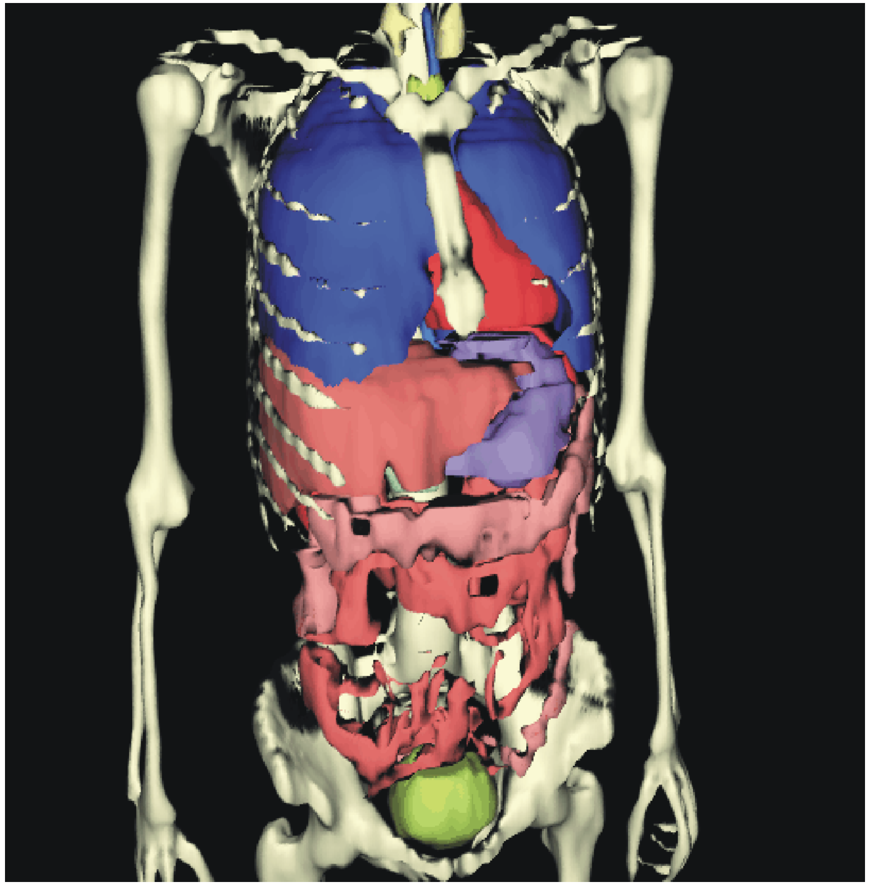
Computational Phantoms
(Helmholtz Zentrum – Munich)

Eva (1979)



Donna (2002)

Golem (2002)

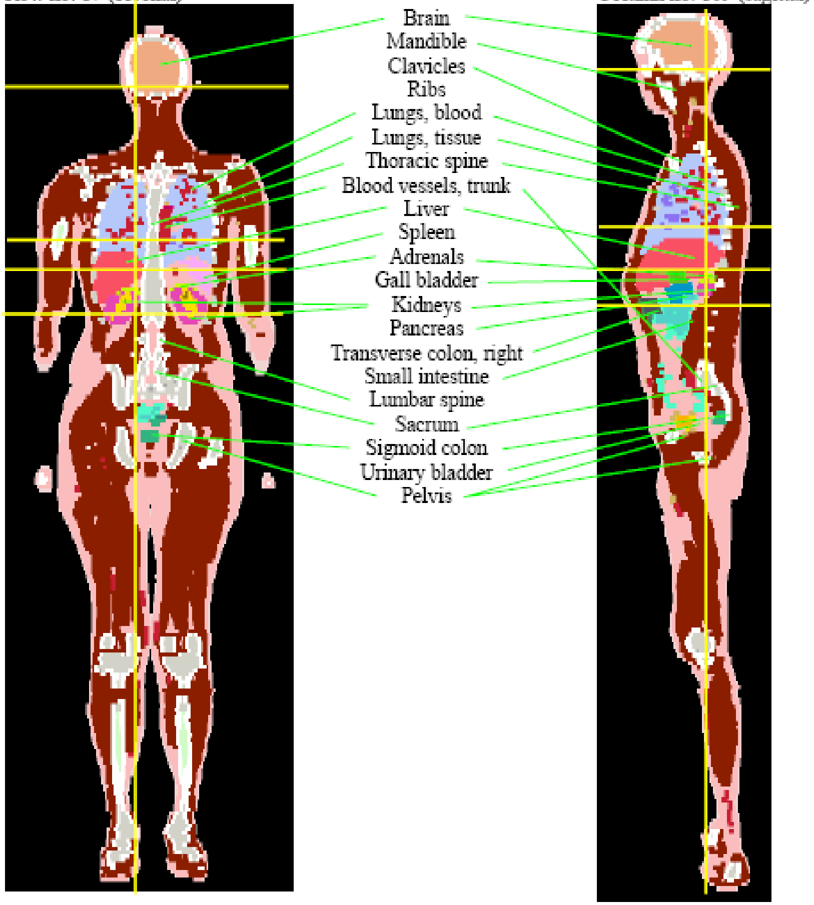


Voxel phantoms (2007)

G.1.2. Coronal and sagittal images

Row no. 87 (coronal)

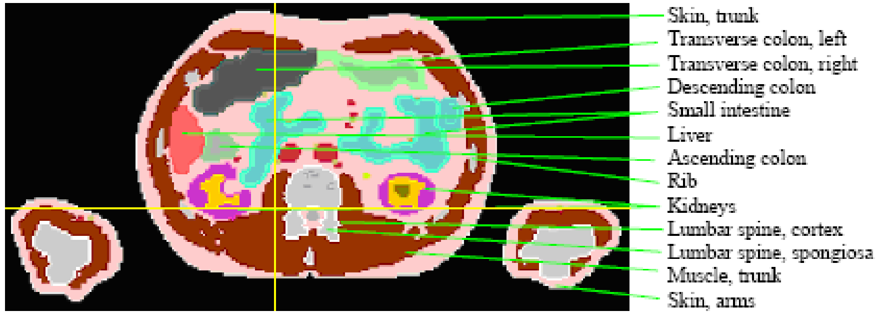
Column no. 109 (sagittal)



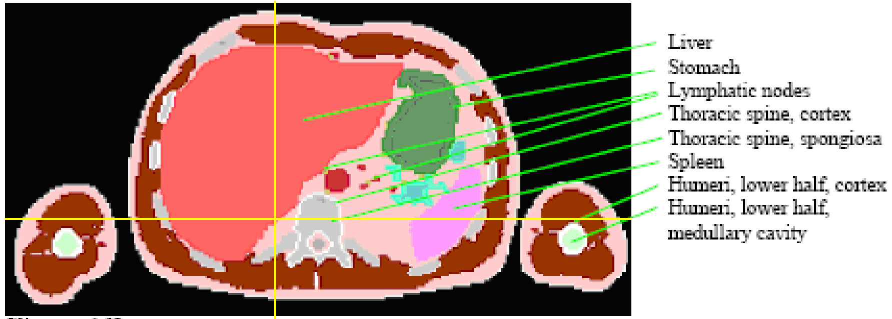
G.1. Images of the male reference computational phantom

G.1.1. Transverse (axial) images

Slice no. 147



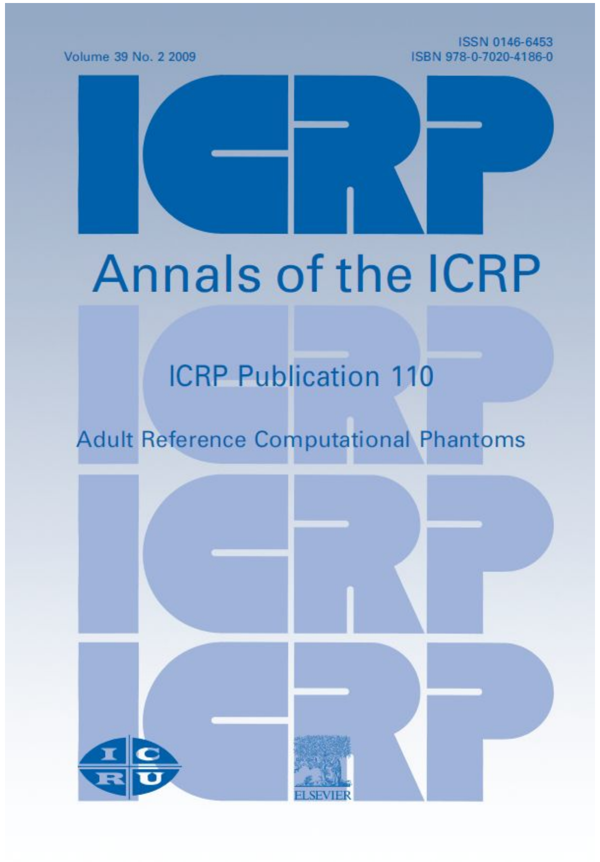
Slice no. 158

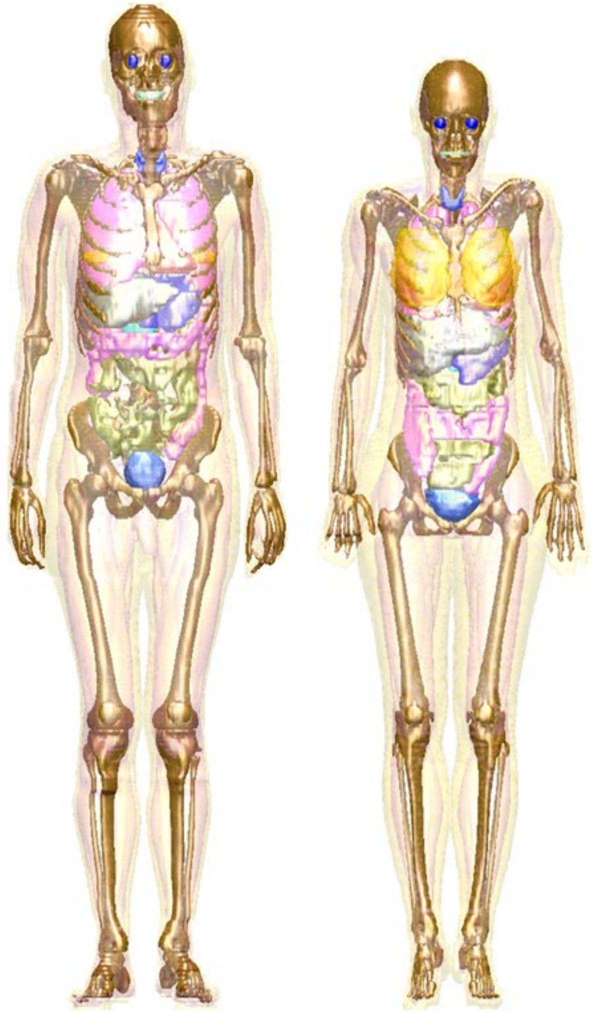


Slice no. 168

ICRP Adult Reference Computational Phantoms – Voxel Based

ICRP Publication 110 (2009)





ICRP 110 - Reference Phantoms Limitations due to image resolution

- Skeletal source and target tissues and some other regions could not be fully segmented or could not be adjusted to their reference masses

Examples:

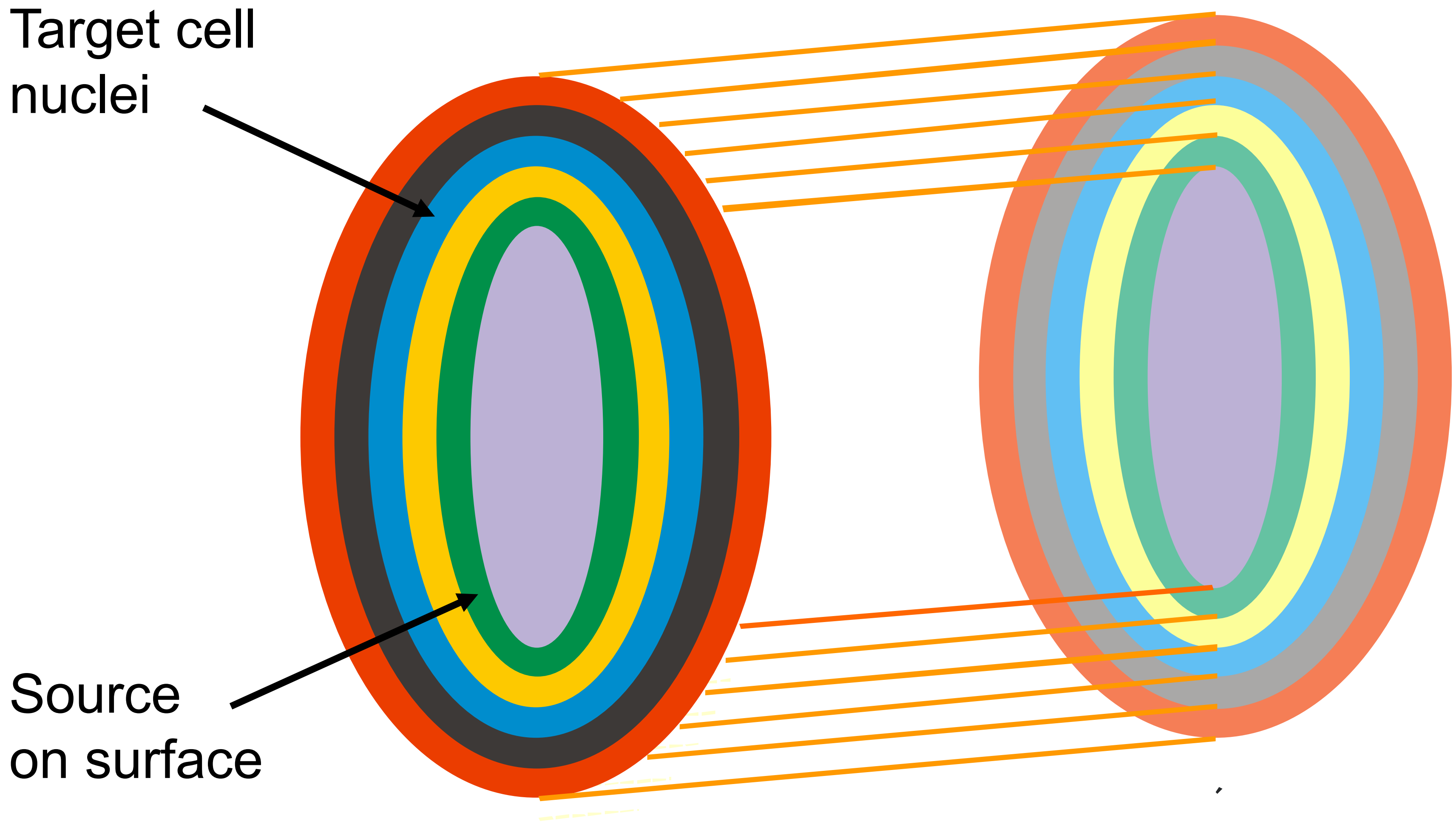
- ET airways (one voxel layer lining the airways of nose, larynx, and pharynx),
- Same for trachea,
- Bronchi were not followed down more than the very first generations of branching,
- The bronchioles are too small to be segmented,
- The skin is represented by a voxel layer, wrapping the phantoms’ exterior,
- The number of residual tissue voxels adjusted to permit matching of the reference total body mass for each phantom.

ICRP 110 - Reference Phantoms
Limitations due to image resolution

Consequences:

- The finite voxel resolution limits their application to short-ranged radiations such as beta and alpha particles. For example, for assessing depth doses in the tissues of the respiratory airways of the Human Respiratory Tract Model or the walls of the stomach, small intestine, or colon of the Human Alimentary Tract Model.

Geometric Model of Airway for Dosimetry



25481

Geometric Model of Oral Cavity

ICRP Publication 100

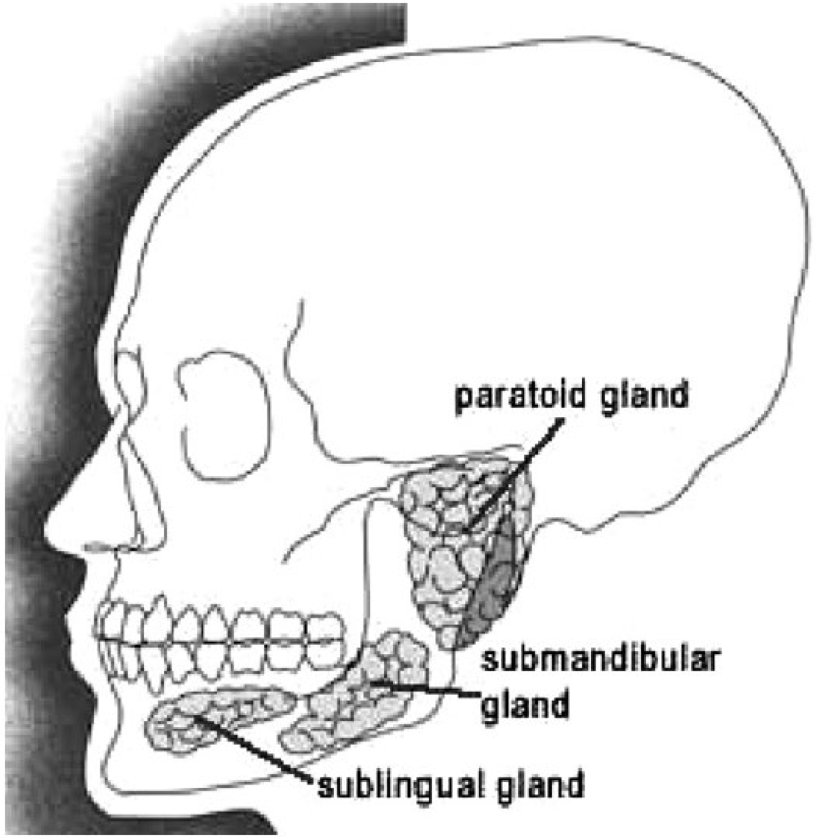
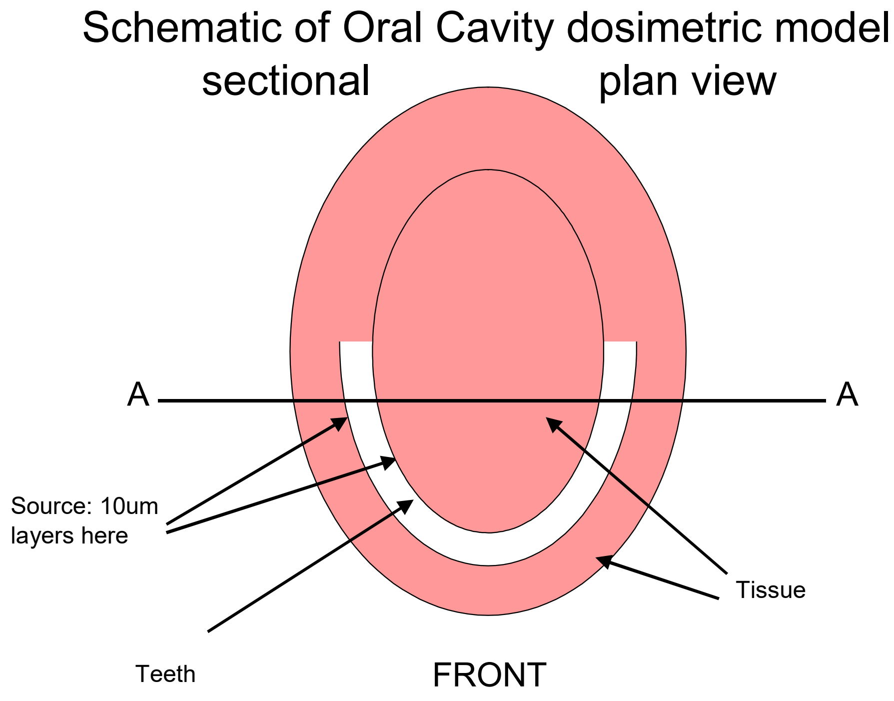


Fig. 7.1. Position and shape of the salivary glands.

Dosimetric Model for Oral Cavity



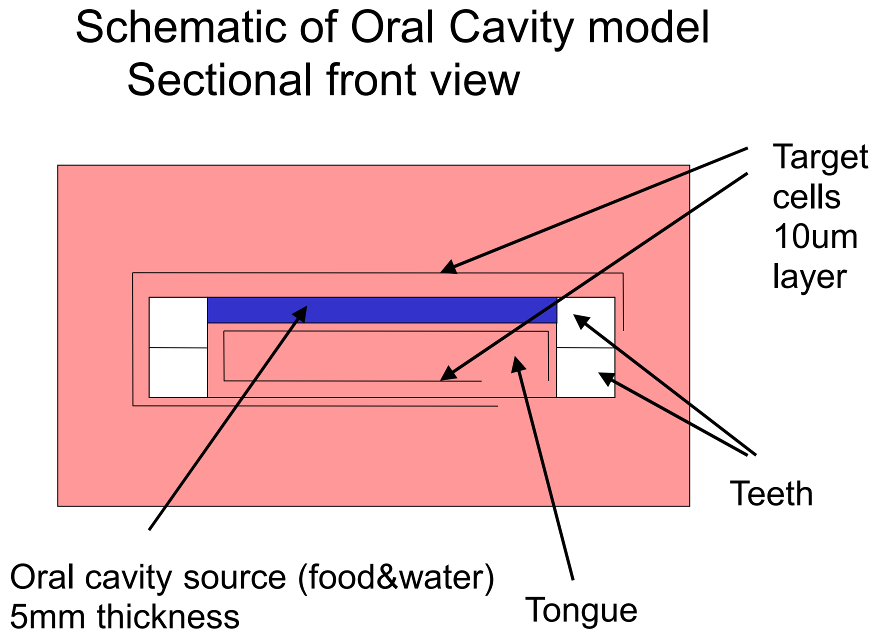
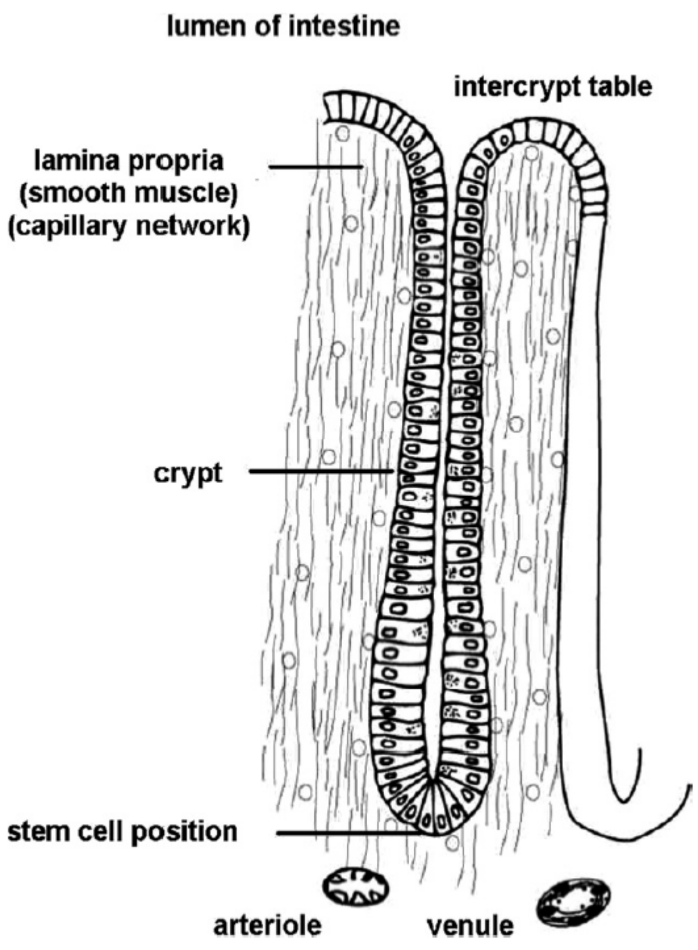
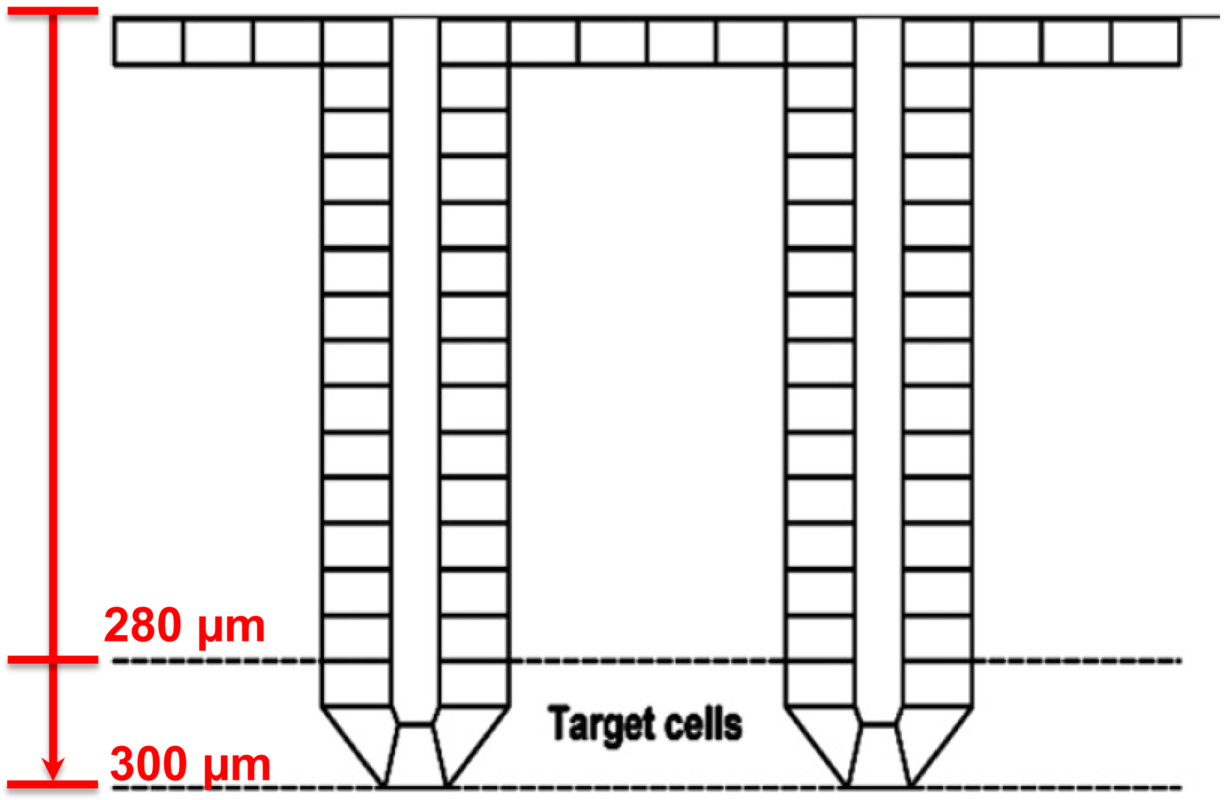
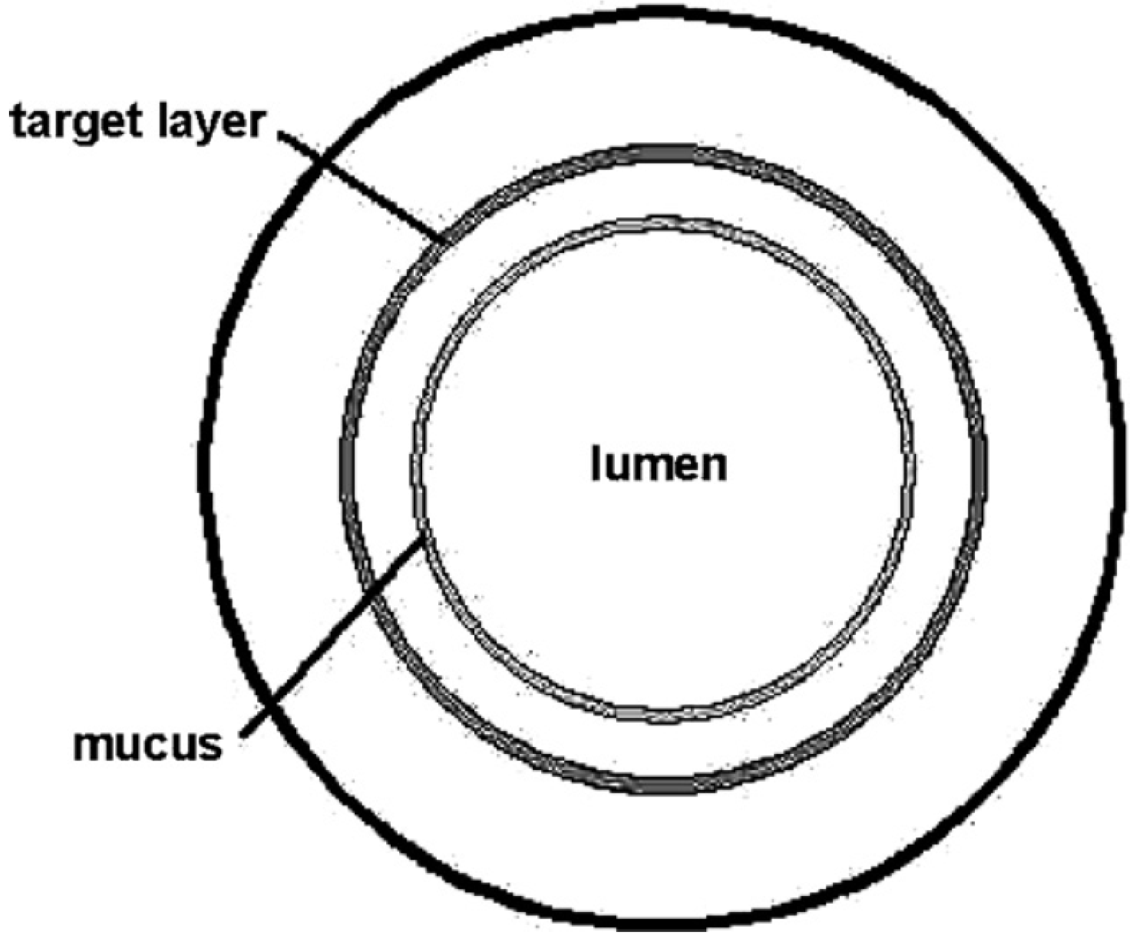


Illustration of the cross-sectional structure of the epithelial lining of the large intestine, showing crypt and stem cell position



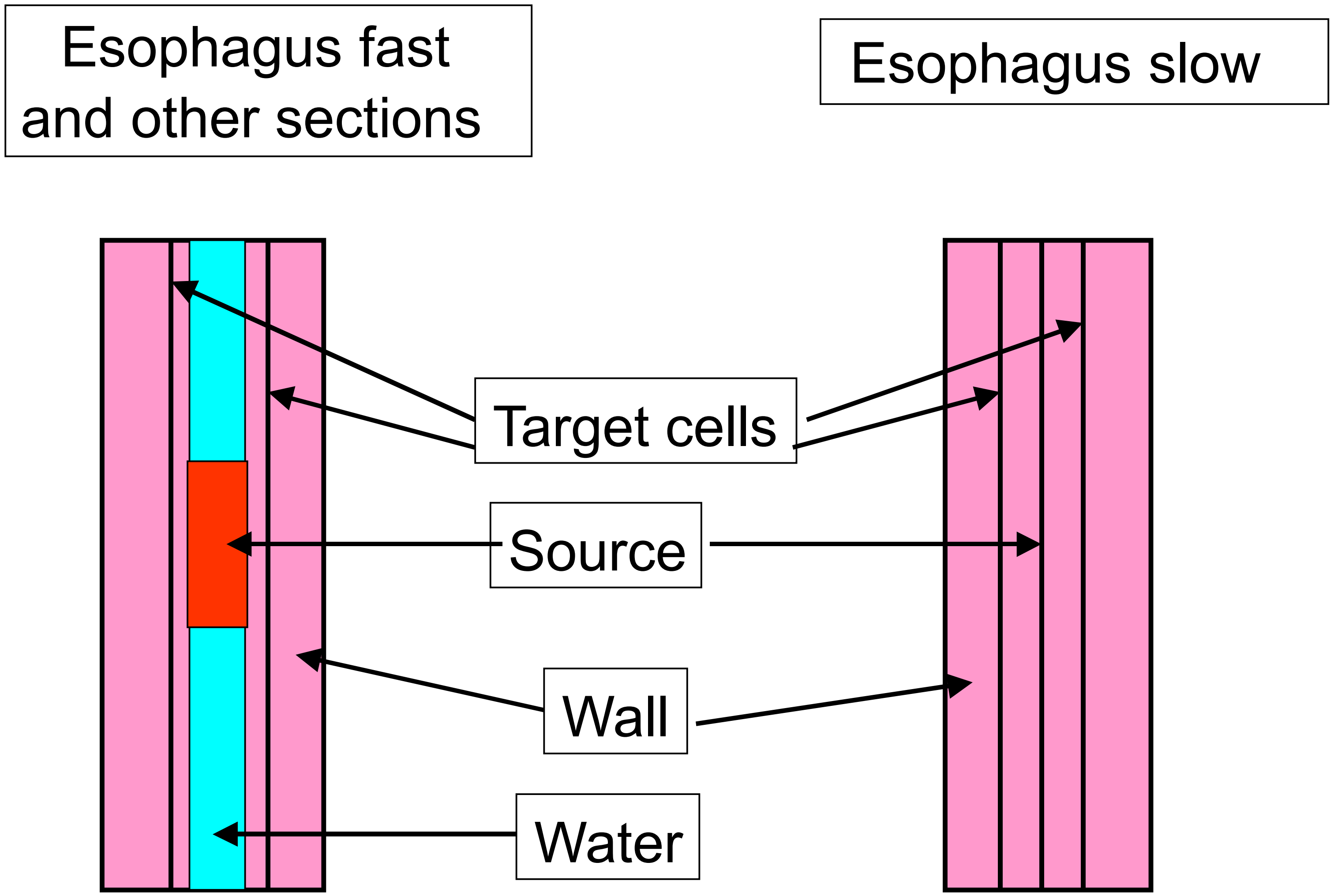


Cross-section of the geometric model used to calculate absorbed fractions for the tubular regions of the alimentary tract



The presence of mucus on the lumenal surface is ignored. Target cells are assumed to form a continuous layer at a defined depth from the lumenal surface.

Dose to Target Cells in the Esophagus



Comparison of Ingestion Dose Coefficients for Sr-90 HATM x ICRP-30 GI Tract model

ICRP Publication 100

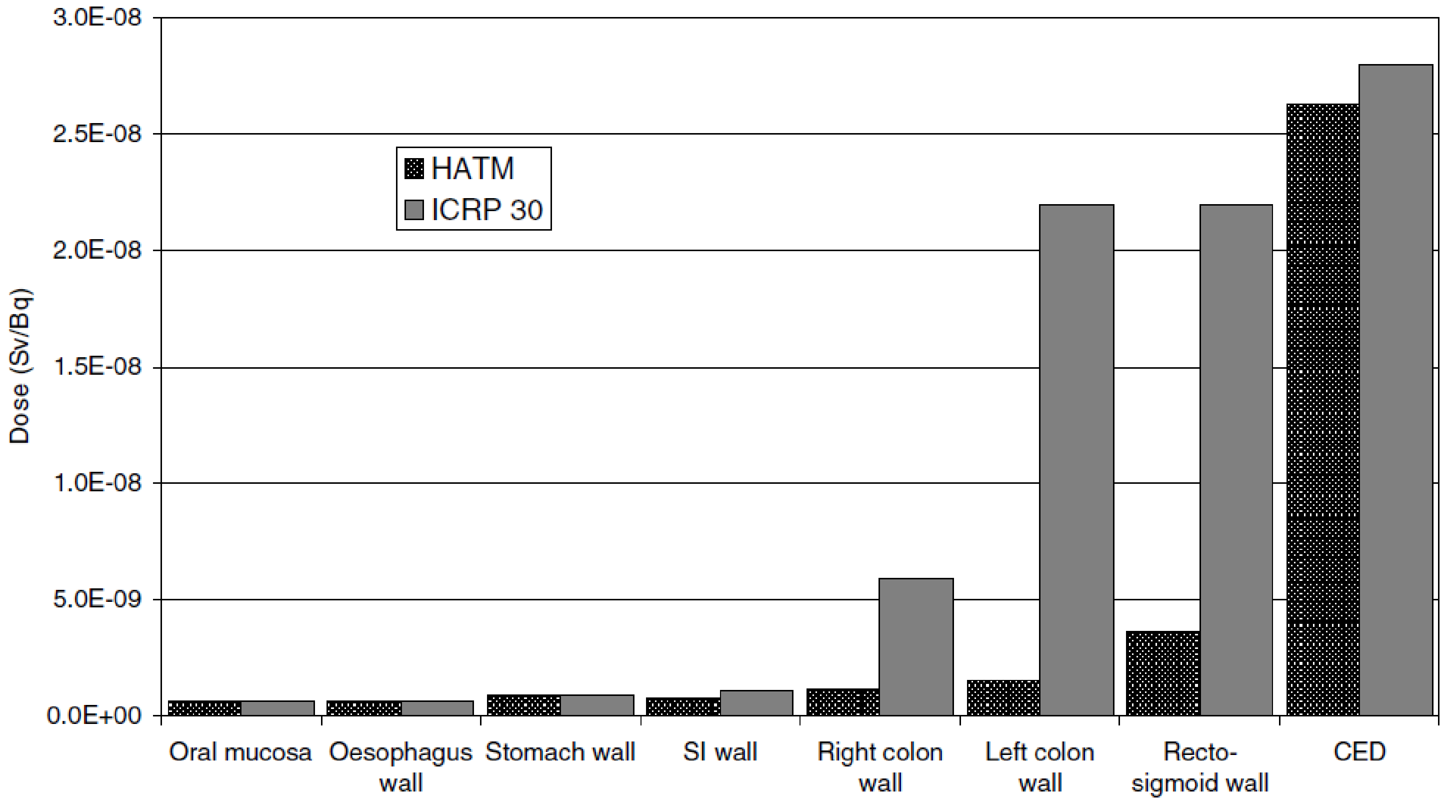


Fig. 8.1. Comparison of dose coefficients calculated using the human alimentary tract model (HATM) and the *Publication 30* model (ICRP 30), considering single acute ingestion of ^{90}Sr by adult males. CED, committed effective dose; SI, small intestine.

Comparison of Ingestion Dose Coefficients for Pu-239 HATM x ICRP-30 GI Tract model

ICRP Publication 100

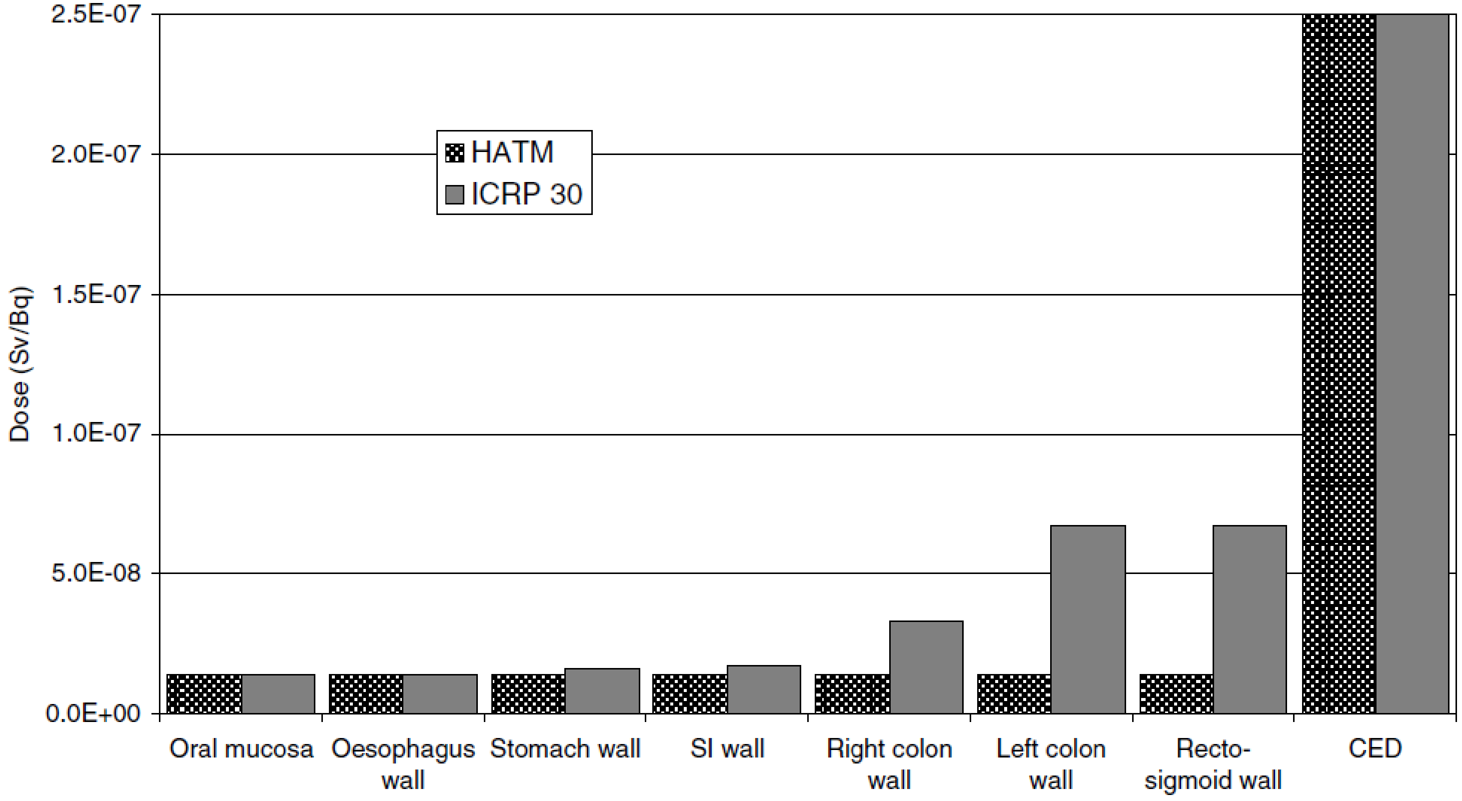


Fig. 8.3. Comparison of dose coefficients calculated using the human alimentary tract model (HATM) and the *Publication 30* model (ICRP 30), considering single acute ingestion of ^{239}Pu by adult males. CED, committed effective dose; SI, small intestine.

Remarks on the Evolution of Internal Dosimetry

- Effects of radiations have been reviewed by ICRP → ICRP-103 (2007).

- Biokinetic and dosimetric models are becoming more and more realistic.

- Specific biokinetic and dosimetric models for internal dose calculations have also been developed for members of the public of all groups of age, including embryo, fetus and nursing infants.

Specific Absorbed Fractions for photons and electrons

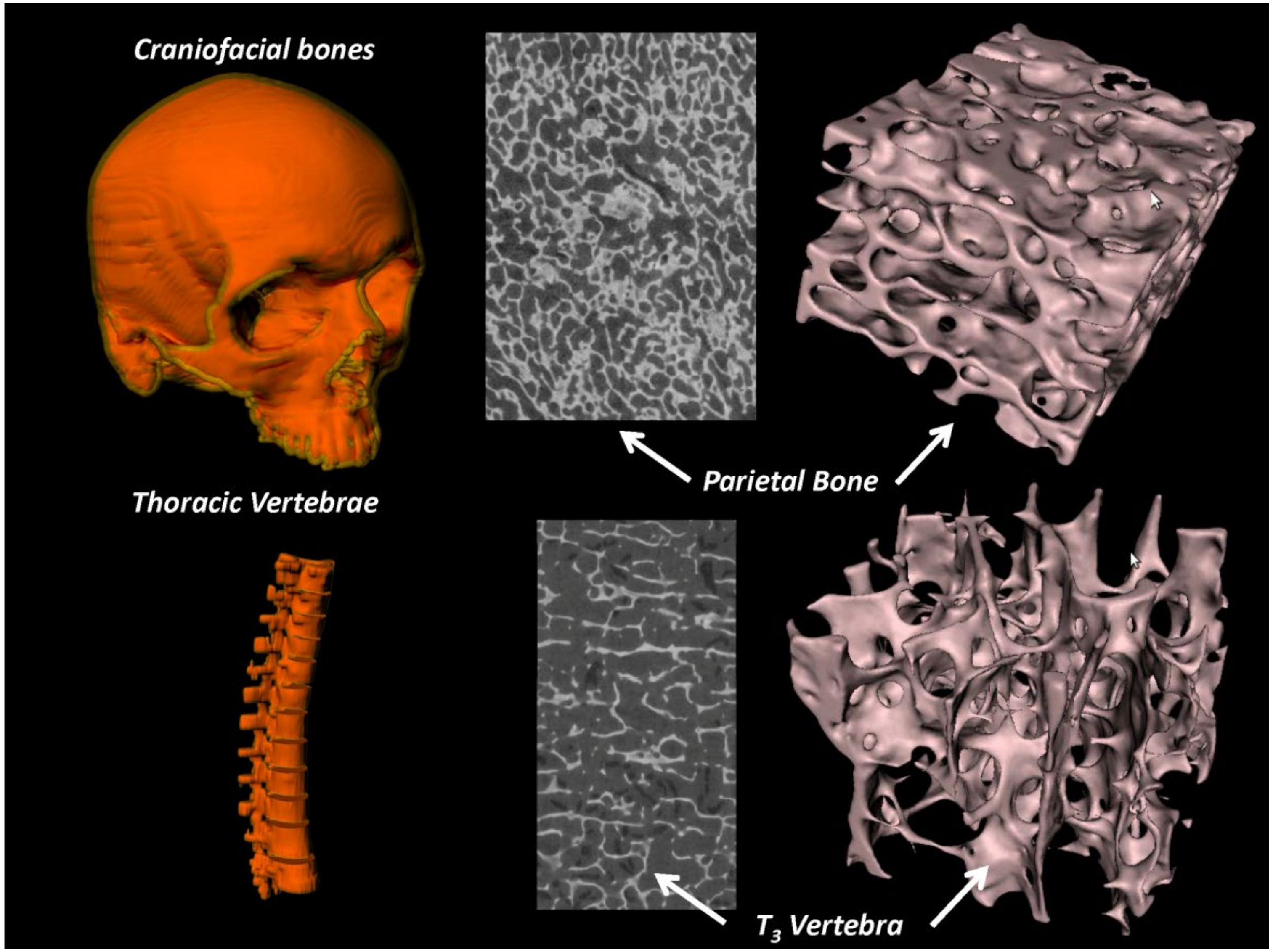
100 Source regions:

O-cavity, O-mucosa, Teeth-S, Teeth-V, Tongue, Tonsils, Oesophag-f, Oesophag-s, Oesophagus, St-cont, St-wall, SI-cont, SI-wall, SI-villi, RC-cont, RC-wall, LC-cont, LC-wall, RSig-cont, RSig-wall, ET1-sur, ET2-sur, ET2-bnd, ET2-seq, LN-ET, Bronchi, Bronchi-f, Bronchi-s, Bronchi-b, Bronchi-q, Bronchiole, Brchiole-f, Brchiole-s, Brchiole-b, Brchiole-q, AI, LN-Th, Lungs, Adrenals, Ht-cont, Blood, C-bone-S, C-bone-V, T-bone-S, T-bone-V, C-marrow, T-marrow, Brain, Breast-a, Breast-g, Breast, Eye-lens, GB-wall, GB-cont, Ht-wall, Kidneys, Liver, Lymph, Muscle, Ovaries, Pancreas, P-gland, Prostate, S-glands, Skin, Sp-cord, Spleen, Testes, Thymus, Thyroid, Ureters, UB-wall, UB-cont, Uterus, Adipose, T-body, S-tissue, ET2-tra, ET2-seq-tra, LN-ET-tra, LN-ET-bnd, BBi-tra, BBi-seq-tra, bbe-tra, bbe-seq-tra, AI-tra, AI-bnd, LN-TH-tra, LN-TH-bnd, BB, bb, Colon, Cartilage, Y-marrow, Misc Bone, R-marrow, Other

69 Target regions:

R-marrow, Colon, Lungs, St-wall, Breast, Ovaries, Testes, UB-wall, Oesophagus, Liver, Thyroid, Endost-BS, Brain, S-glands, Skin, Adrenals, ET, GB-wall, Ht-wall, Kidneys, Lymph, Muscle, O-mucosa, Pancreas, Prostate, SI-wall, Spleen, Thymus, Uterus, Tongue, Tonsils, RC-wall, LC-wall, RSig-wall, ET1-bas, ET2-bas, LN-ET, Bronch-bas, Bronch-sec, Bchiol-sec, AI, LN-Th, RLung, LLung, RAdrenal, LAdrenal, RBreast-a, RBreast-g, LBreast-a, LBreast-g, RBreast, LBreast, Breast-a, Breast-g, Eye-lens, RKidney-C, RKidney-M, RKidney-P, Rkidney, LKidney-C, LKidney-M, LKidney-P, Lkidney, Rovary, Lovary, P-gland, Sp-cord, Ureters, Adipose

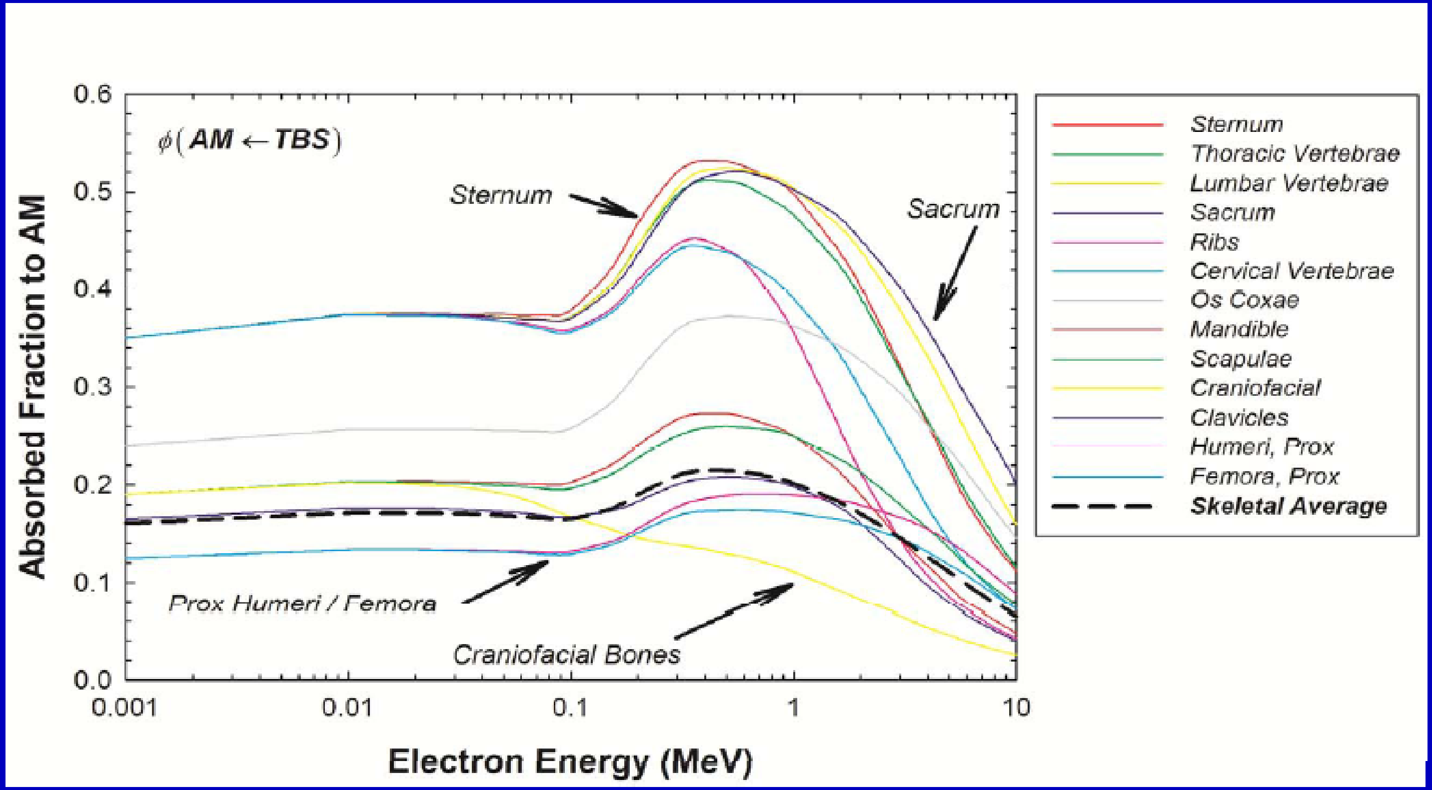
Skeletal Dosimetry Models



INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

DOCAL – C2 Task Group on Dose Calculations

ϕ (AM ← TBS)



Target – Active (Red) Marrow   *Source – Trabecular Bone Surfaces*

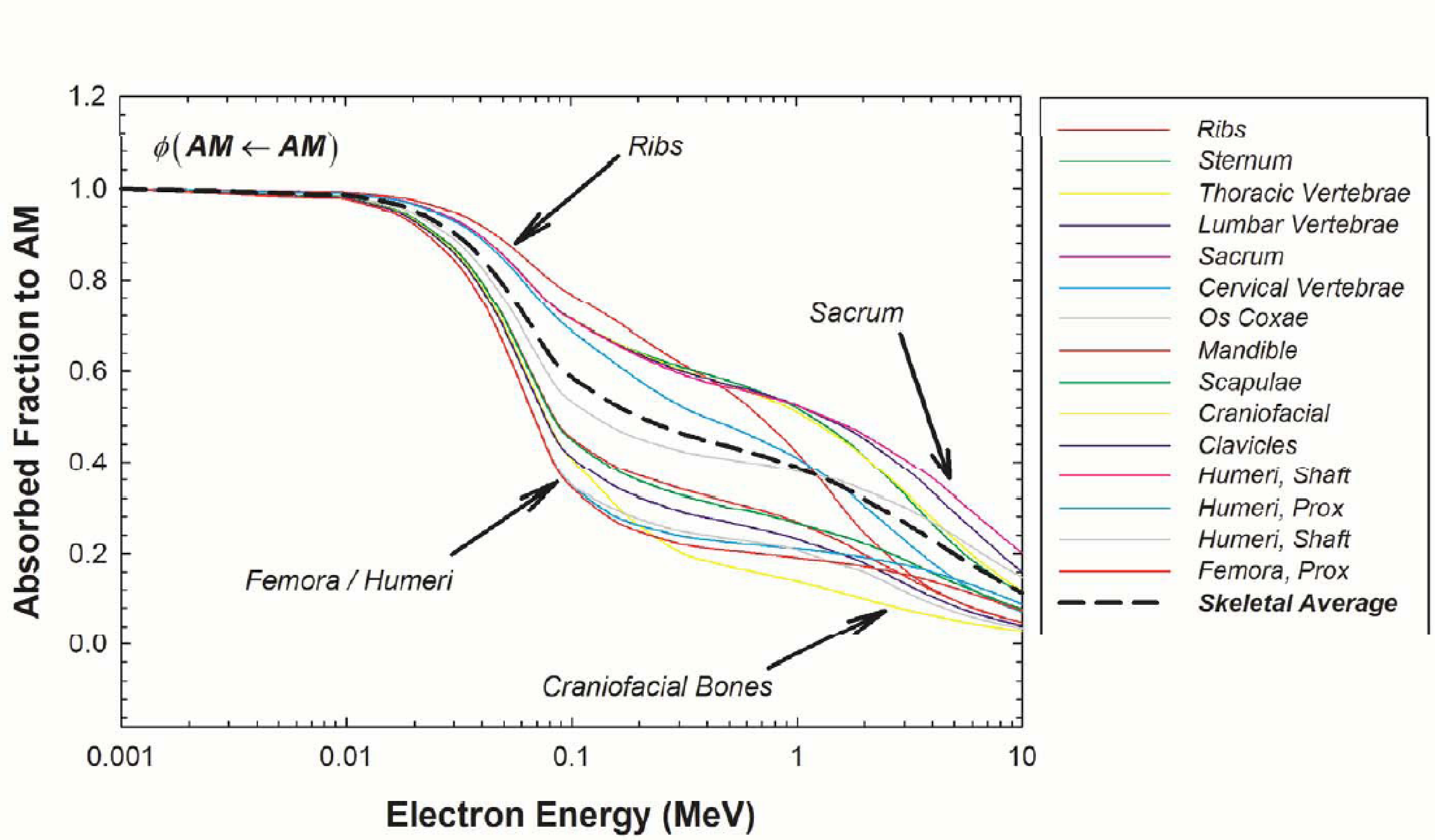
Sources: Active (Red) Marrow, Inactive (Yellow) Marrow, Trabecular Bone Surfaces, Trabecular Bone Volume, Cortical Bone Surfaces, Cortical Bone Volume

Targets: Active (Red) Marrow, Endosteum (TM50)

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

DOCAL – C2 Task Group on Dose Calculations

$\phi(AM \leftarrow AM)$



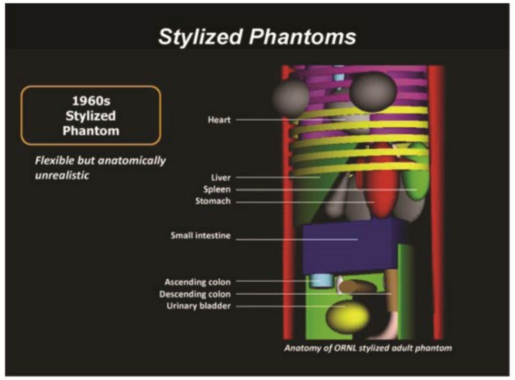
Target – Active (Red) Marrow *Source – Active (Red) Marrow*

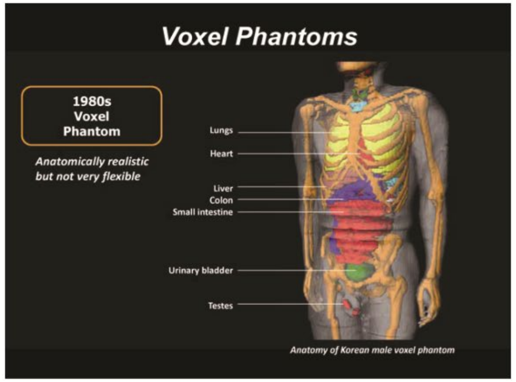
Phantom Evolution

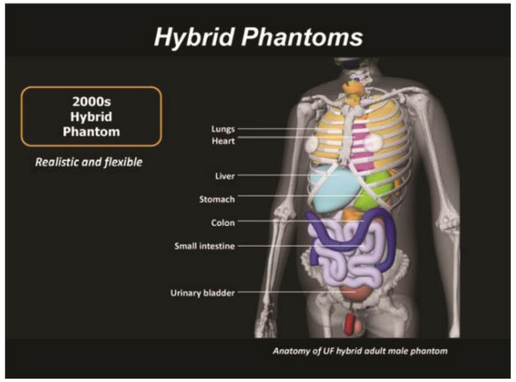
Stylized Phantoms
Organ / body contours defined by 3D mathematical surface equations

Voxel Phantoms
Organs and body tissues defined by groupings of 3D arrays of tagged image volume elements

Hybrid Phantoms
Organ / body contours defined by NURBS or polygon mesh surfaces





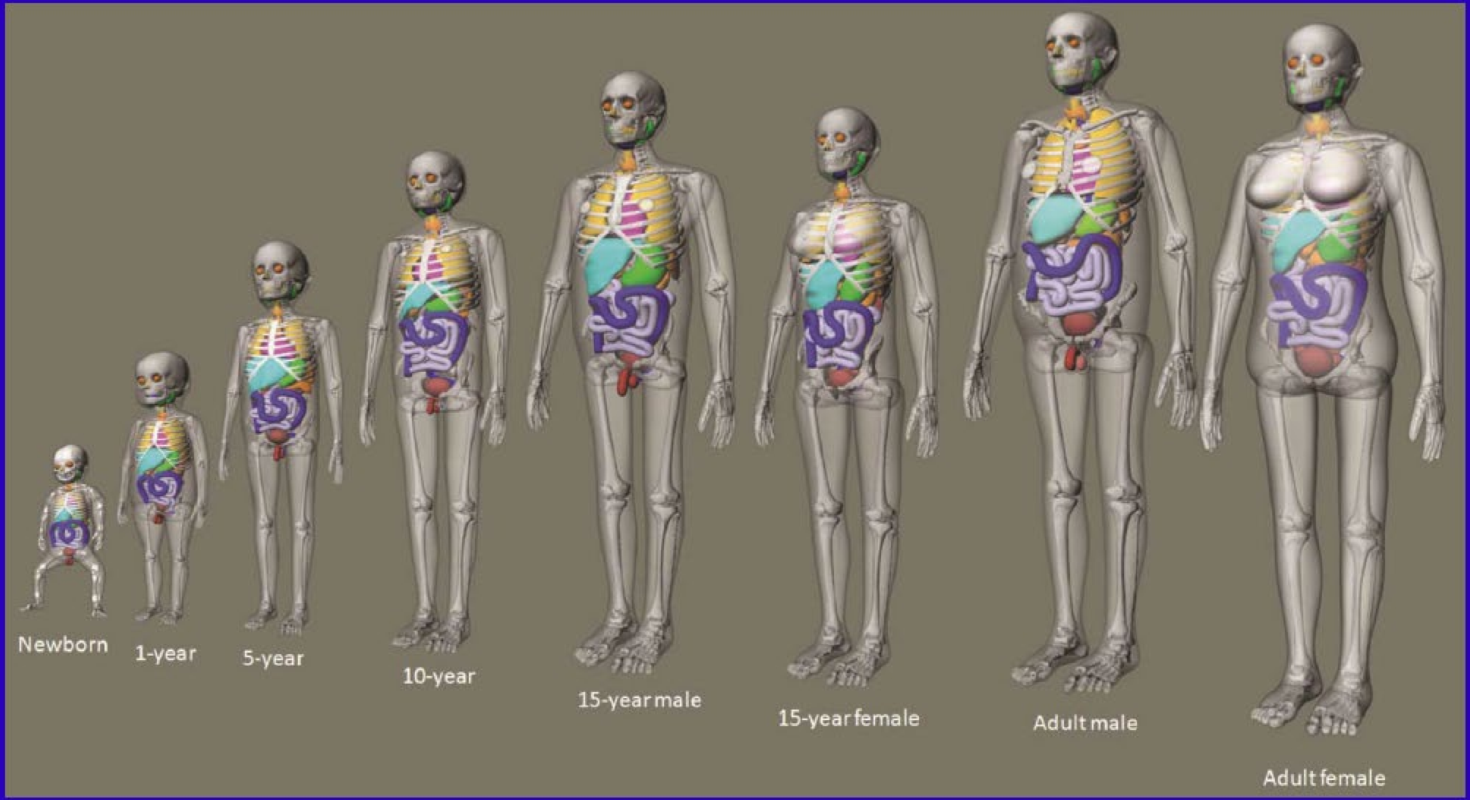


Non-uniform rational basis spline (**NURBS**) is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

DOCAL – C2 Task Group on Dose Calculations

Pediatric Hybrid Phantoms



The UF family of reference hybrid phantoms for computational radiation dosimetry

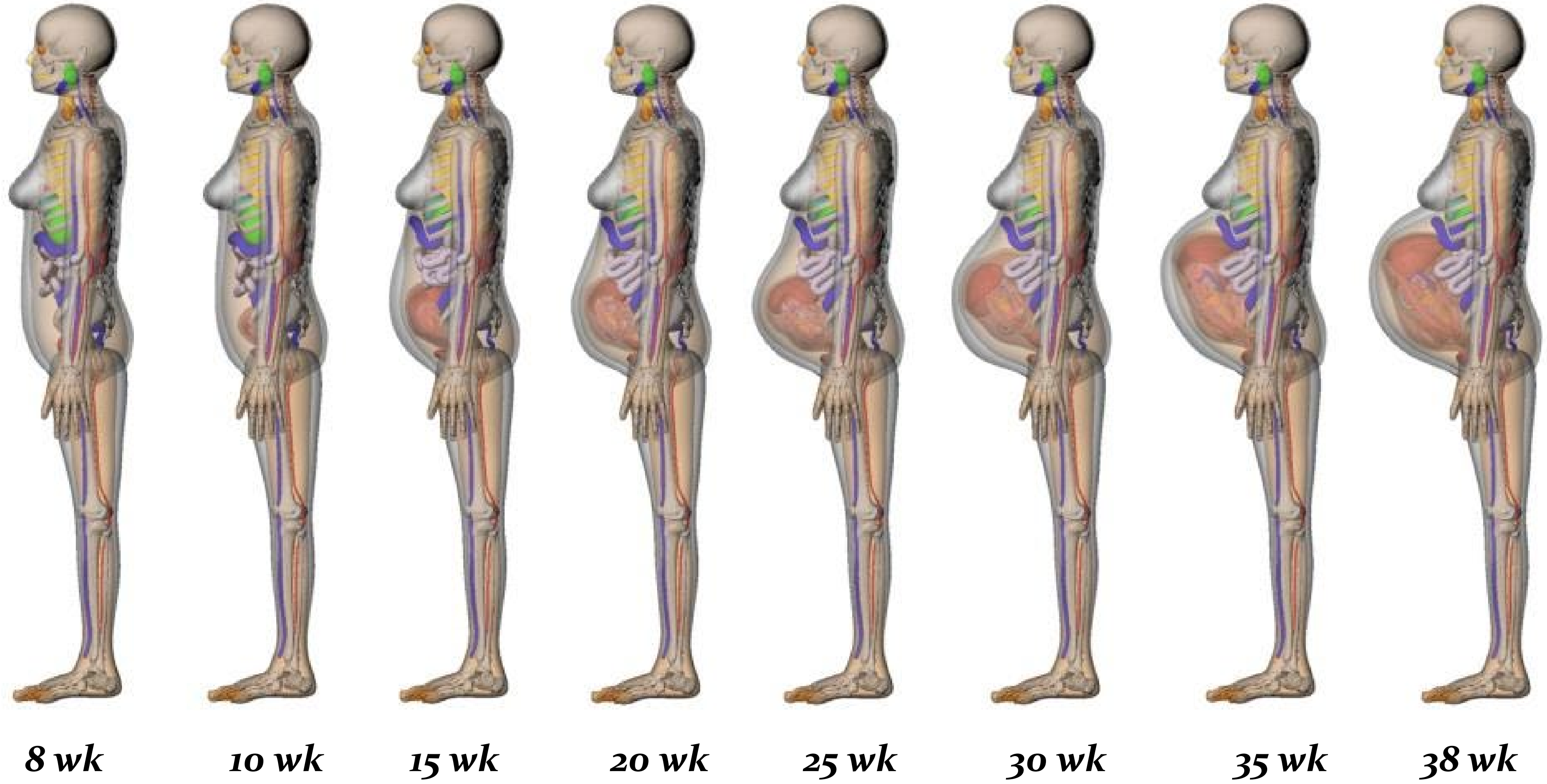
Choonsik Lee[1], Daniel Lodwick[2], Jorge Hurtado[2], Deanna Pafundi[2], Jonathan L Williams[3] and Wesley E Bolch[4,5]

IOP Publishing

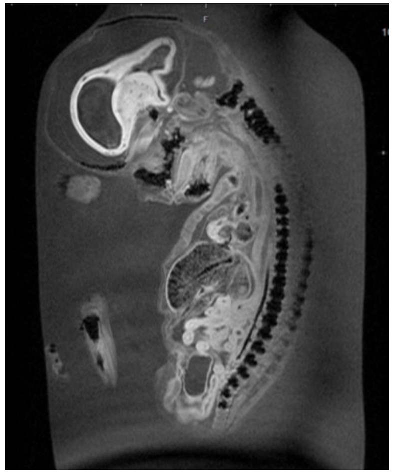
Phys. Med. Biol. 55 (2010) 339–363

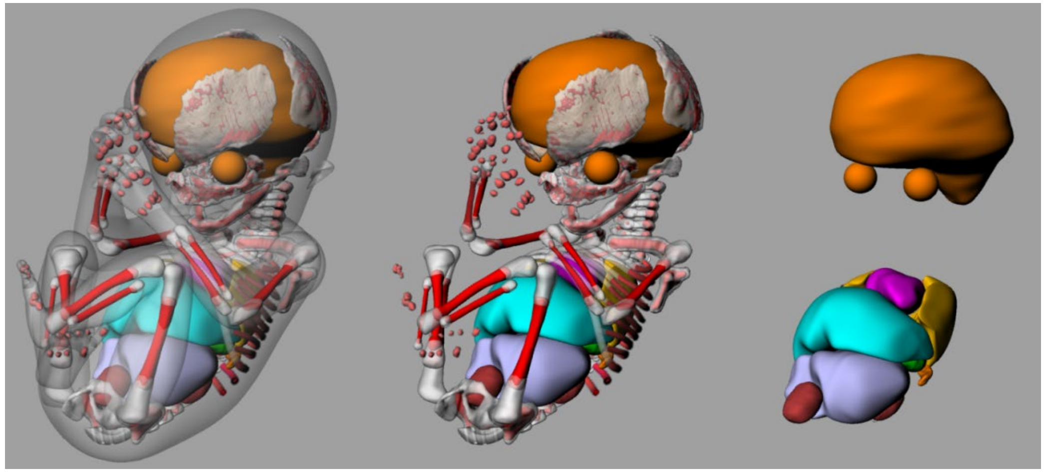
ICRP Computational Phantoms – Pediatric

Proposed – Fetal and Pregnant Female Series



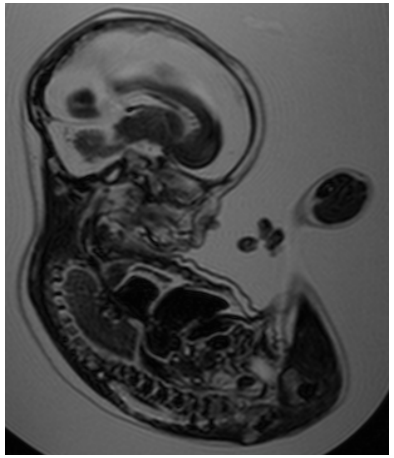
Fetal Model Development

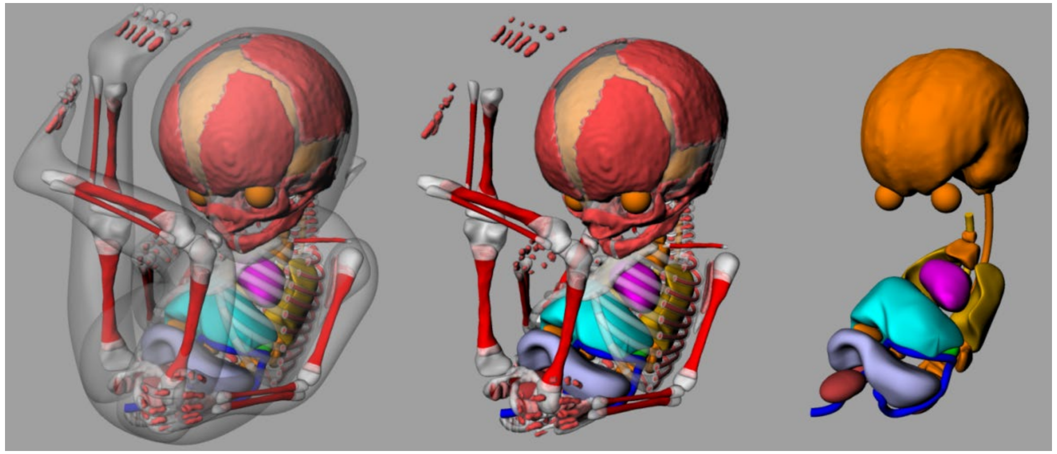




4.7 T NMR Image – 11.5 week
11.5 week fetus

Two Specimen-Specific Fetal Models





1.5 T MR Image – 21 week
21 week fetus

Dosimetric Quantities and Limits

Establishment of a Dosimetric System

Physical Effect	→	Biological Effect	→	Health Effect
Radioactive Decay (α, β, γ, neutron, etc.)		DNA Breaks		Risk of death by cancer Risk of hereditary effects Noncarcinogenic Effects

D: absorbed dose

radiation

H: equivalent dose

risk

Committed equivalent dose [$H_T(50)$]

The time integral of the equivalent dose rate in a target organ or tissue T of the Reference Adult Male or the Reference Adult Female.

$$H_{\mathrm{T}}(50) = \int_0^{50} \dot{H}(r_{\mathrm{T}}, t)\mathrm{d}t \qquad \text{(Sv)}$$

For both sexes, the equivalent dose rate $\dot{H}(r_T,t)$ in target region r_T at time t after an acute intake is expressed as:

$$\dot{H}(r_{\mathrm{T}}, t) = \sum_{r_{\mathrm{S}}} A(r_{\mathrm{S}}, t) \cdot S_{\mathrm{w}}(r_{\mathrm{T}} \leftarrow r_{\mathrm{S}})$$

$A(r_S, t)$ is the activity of the radionuclide in source region r_S at time t after intake, in Bq

$S_w(r_T \leftarrow r_S)$ is the radiation weighted S coefficient (i.e. the equivalent dose to target region r_T per nuclear transformation in source region r_S), in Sv $(\mathrm{Bq\ s})^{-1}$

S coefficient (radiation weighted) [$S_w(r_T \leftarrow r_S)$]

The equivalent dose to target region r_T per nuclear transformation of a given radionuclide in source region r_S, Sv (Bq s)$^{-1}$, for the Reference Male and the Reference Female.

$$S_w(r_T \leftarrow r_S) = \sum_R w_R \sum_i E_{R,i} Y_{R,i} \Phi\left(r_T \leftarrow r_S, E_{R,i}\right)$$

where:

$E_{R,i}$ is the energy, in joules, of the i^{th} radiation of type R emitted in nuclear transformations of the radionuclide.

$Y_{R,i}$ is the yield of the i^{th} radiation of type R per nuclear transformation (Bq s)$^{-1}$.

w_R is the radiation weighting factor for radiation type R.

$\Phi(r_T \leftarrow r_S, E_{R,i})$ is the specific absorbed fraction, defined as the fraction of energy $E_{R,i}$ of radiation type R emitted within the source region r_S that is absorbed per mass in the target region r_T, kg^{-1}.

Radiation weighting factor (w_R)

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Table 2. Recommended radiation weighting factors.

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons[a] and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see Fig. 1 and Eq. 4.3)

All values relate to the radiation incident on the body or, for internal radiation sources, emitted from the incorporated radionuclide(s).

[a] Note the special issue of Auger electrons discussed in paragraph 116 and in Section B.3.3 of Annex B.

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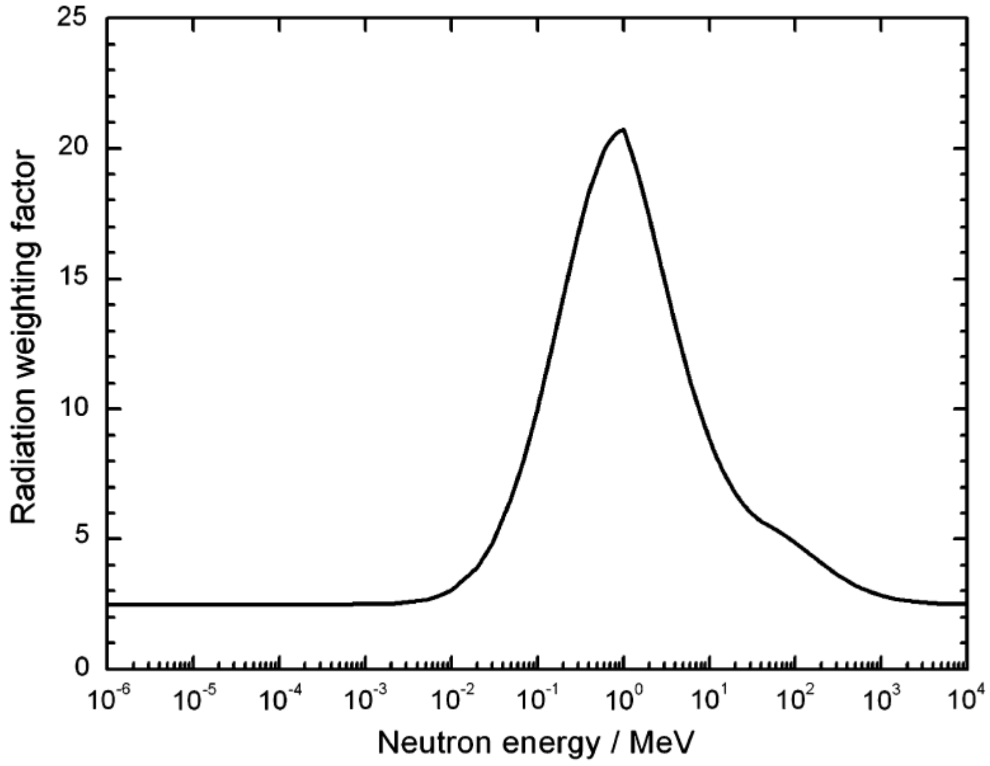

Fig. 1. Radiation weighting factor, w_R, for neutrons versus neutron energy.

Specific Absorbed Fractions ($\Phi(r_T \leftarrow r_S, E_{R,i})$)

(alphas, electrons, neutrons and photons for the Adult Male and the Female)

```
Specific absorbed fractions of energy (1/kg)
Adult Male Reference Computational Phantom
Photons
  43  79              0.0       0.001     0.005     0.010     0.015     0.020     0.030     0.040     0.050     0.060     0.08(
-----------------------------------------------------------------------------------------------------------------------------
O-mucosa   <-O-cavity  0.0       7.558E-04 9.579E-01 2.078E+01 1.345E+01 8.344E+00 3.548E+00 2.022E+00 1.308E+00 9.700E-01 8.105E-
Oesophagus<-O-cavity  0.0       1.842E-08 5.701E-07 2.500E-06 6.230E-04 2.821E-03 6.553E-03 7.137E-03 7.380E-03 7.196E-03 6.982E-
St-stem    <-O-cavity  0.0       0.0       0.0       0.0       0.0       0.0       1.074E-05 9.734E-05 1.955E-04 2.893E-04 3.521E-
SI-stem    <-O-cavity  0.0       0.0       0.0       0.0       0.0       0.0       3.100E-07 6.477E-06 1.752E-05 3.094E-05 4.669E-
RC-stem    <-O-cavity  0.0       0.0       0.0       0.0       0.0       0.0       1.407E-06 1.029E-05 3.104E-05 5.168E-05 6.854E-
LC-stem    <-O-cavity  0.0       0.0       0.0       0.0       0.0       0.0       2.394E-06 1.814E-05 5.000E-05 9.263E-05 1.180E-
RS-stem    <-O-cavity  0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       1.483E-06 2.490E-
ET1-bas    <-O-cavity  0.0       1.581E-07 1.038E-05 6.289E-05 9.597E-03 2.856E-02 6.152E-02 6.654E-02 6.789E-02 6.446E-02 6.198E-
ET2-bas    <-O-cavity  0.0       4.416E-05 2.074E-02 2.935E-01 5.314E-01 5.661E-01 4.106E-01 2.904E-01 2.185E-01 1.750E-01 1.512E-
LN-ET      <-O-cavity  0.0       2.889E-05 1.170E-02 1.553E-01 3.807E-01 4.433E-01 3.397E-01 2.455E-01 1.861E-01 1.461E-01 1.223E-
Bronch-bas<-O-cavity  0.0       0.0       0.0       0.0       0.0       4.510E-06 3.176E-04 9.196E-04 1.343E-03 1.607E-03 1.839E-
Bronch-sec<-O-cavity  0.0       0.0       0.0       0.0       0.0       4.510E-06 3.176E-04 9.196E-04 1.343E-03 1.607E-03 1.839E-
Bchiol-sec<-O-cavity  0.0       0.0       0.0       0.0       0.0       4.157E-06 2.253E-04 7.413E-04 1.152E-03 1.380E-03 1.582E-
AI         <-O-cavity  0.0       0.0       0.0       0.0       0.0       4.157E-06 2.253E-04 7.413E-04 1.152E-03 1.380E-03 1.582E-
LN-Th      <-O-cavity  0.0       0.0       0.0       0.0       0.0       2.958E-04 2.931E-03 4.116E-03 4.825E-03 5.376E-03 5.569E-
R-marrow   <-O-cavity  0.0       8.234E-07 9.616E-05 7.471E-04 1.892E-03 3.281E-03 5.699E-03 6.176E-03 6.357E-03 6.206E-03 6.012E-
Endost-BS  <-O-cavity  0.0       1.117E-06 1.451E-04 1.180E-03 3.058E-03 4.939E-03 7.516E-03 8.414E-03 8.912E-03 8.790E-03 8.371E-
Brain      <-O-cavity  0.0       2.548E-08 8.832E-07 4.067E-06 1.713E-04 1.288E-03 7.559E-03 1.191E-02 1.572E-02 1.707E-02 1.730E-
Eye-lens   <-O-cavity  0.0       0.0       0.0       0.0       2.607E-04 3.366E-03 2.420E-02 3.597E-02 3.456E-02 3.442E-02 3.448E-
P-gland    <-O-cavity  0.0       4.824E-07 4.673E-05 3.350E-04 8.632E-03 4.226E-02 7.638E-02 7.488E-02 7.067E-02 6.568E-02 5.939E-
Tongue     <-O-cavity  0.0       4.672E-04 5.005E-01 1.010E+01 7.924E+00 5.758E+00 2.833E+00 1.675E+00 1.106E+00 8.211E-01 6.814E-
Tonsils    <-O-cavity  0.0       3.753E-06 7.449E-04 7.272E-03 1.350E-01 3.171E-01 3.367E-01 2.606E-01 2.051E-01 1.656E-01 1.424E-
S-glands   <-O-cavity  0.0       9.136E-07 1.107E-04 8.733E-04 8.800E-03 3.103E-02 6.008E-02 5.951E-02 5.689E-02 5.233E-02 4.851E-
Thyroid    <-O-cavity  0.0       0.0       0.0       0.0       5.003E-06 5.019E-04 6.297E-03 1.177E-02 1.282E-02 1.315E-02 1.273E-
Breast     <-O-cavity  0.0       0.0       0.0       0.0       7.940E-06 4.059E-05 4.237E-04 7.371E-04 8.737E-04 9.993E-04 1.062E-
```

Committed effective dose [E(50)]

The committed effective dose E(50) is calculated with the use of male and female committed equivalent doses to individual target organs or tissues T according to the expression:

$$E_{(50)} = \sum_{T} w_{\mathrm{T}} \cdot \left[\frac{H_{\mathrm{T}}^{\mathrm{M}}(50) + H_{\mathrm{T}}^{\mathrm{F}}(50)}{2} \right] \qquad (\mathrm{Sv})$$

Calculation of effective dose according to ICRP-103

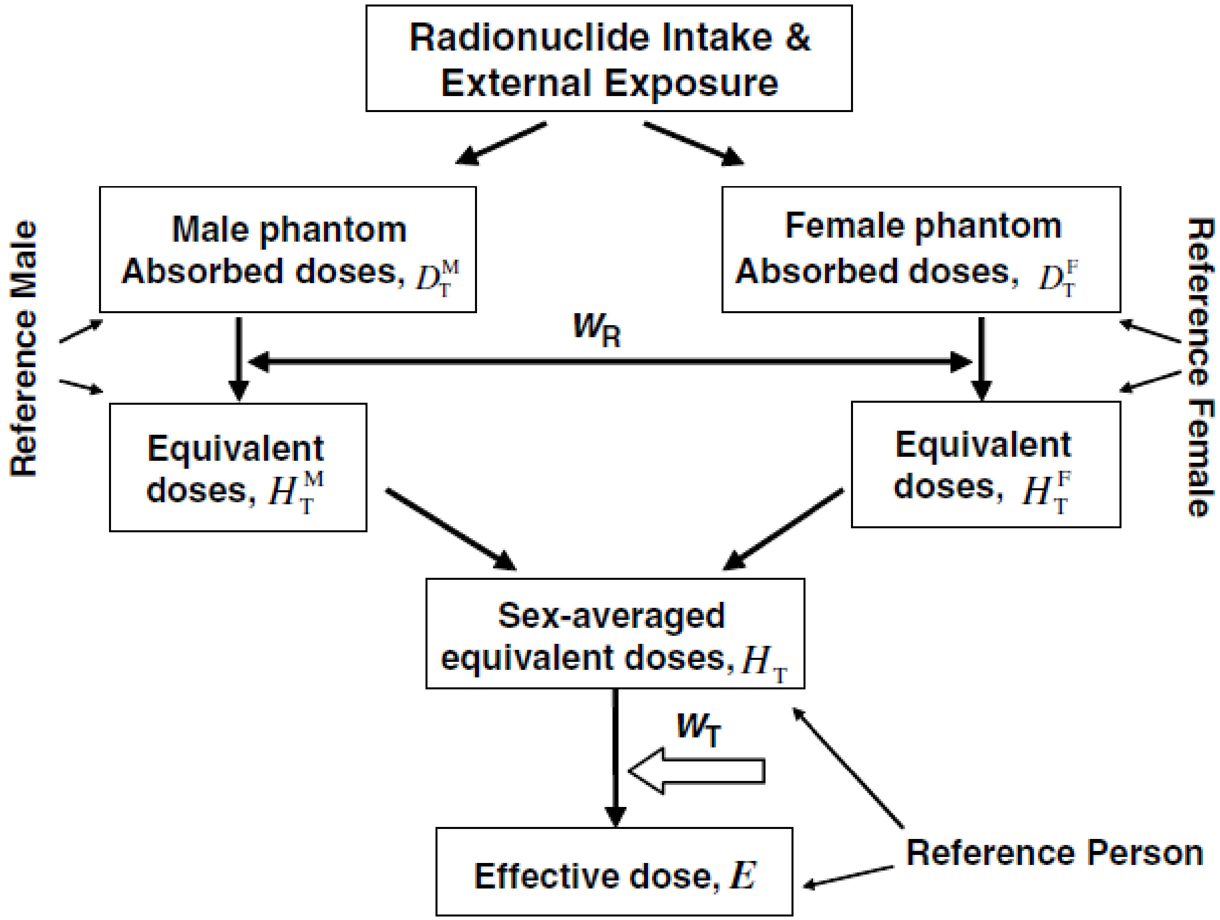

Fig. B.3. Sex – averaging in the calculation of effective dose (E).

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Comparison of the tissue weighting factors proposed by ICRP Publications 26 (1977), 60 (1990) and 103 (2007)

Organ or Tissue	Weighting factor ICRP-26 W_T	ICRP-60 W_T	ICRP-103 W_T
Gonads	0.25	0.20	0.08
Breast	0.15	0.05	0.12
Red Marrow	0.12	0.12	0.12
Lungs	0.12	0.12	0.12
Bone Surface	0.03	0.01	0.01
Thyroid	0.03	0.05	0.04
Bladder	----	0.05	0.04
Colon	----	0.12	0.12
Liver	----	0.05	0.04
Esophagus	----	0.05	0.04
Skin	----	0.01	0.01
Stomach	----	0.12	0.12
Brain	----	----	0.01
Salivary Glands	----	----	0.01
Remainder (*)	0.30	0.05	0.12
Total	1.00	1.00	1.00

ICRP-26 Remainder tissues (Choice of 5):
Adrenals, Bladder, Brain, Stomach, Small Intestine, Upper Large Int., Lower Large Int., Kidneys, Liver, Muscle, Pancreas, Skin, Spleen, Thymus, Uterus.

ICRP-60 Remainder tissues (All 10):
Adrenals, Brain, Extrathoracic (ET) region, Kidneys, Muscle, Pancreas, Small intestine, Spleen, Thymus, Uterus.

ICRP-103 Remainder tissues (All 13):
Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate (♂), Small intestine, Spleen, Thymus, Uterus/cervix (♀).

Recommended Dosed Limits – ICRP-60 (1990) and ICRP-103 (2007)

Table 6. Recommended dose limits[1]

Application	Dose limit Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of 5 years[2]	1 mSv in a year[3]
Annual equivalent dose in		
the lens of the eye	150 mSv	15 mSv
the skin[4]	500 mSv	50 mSv
the hands and feet	500 mSv	–

[1] The limits apply to the sum of the relevant doses from external exposure in the specified period and the 50-year committed dose (to age 70 years for children) from intakes in the same period (see paragraph 143).

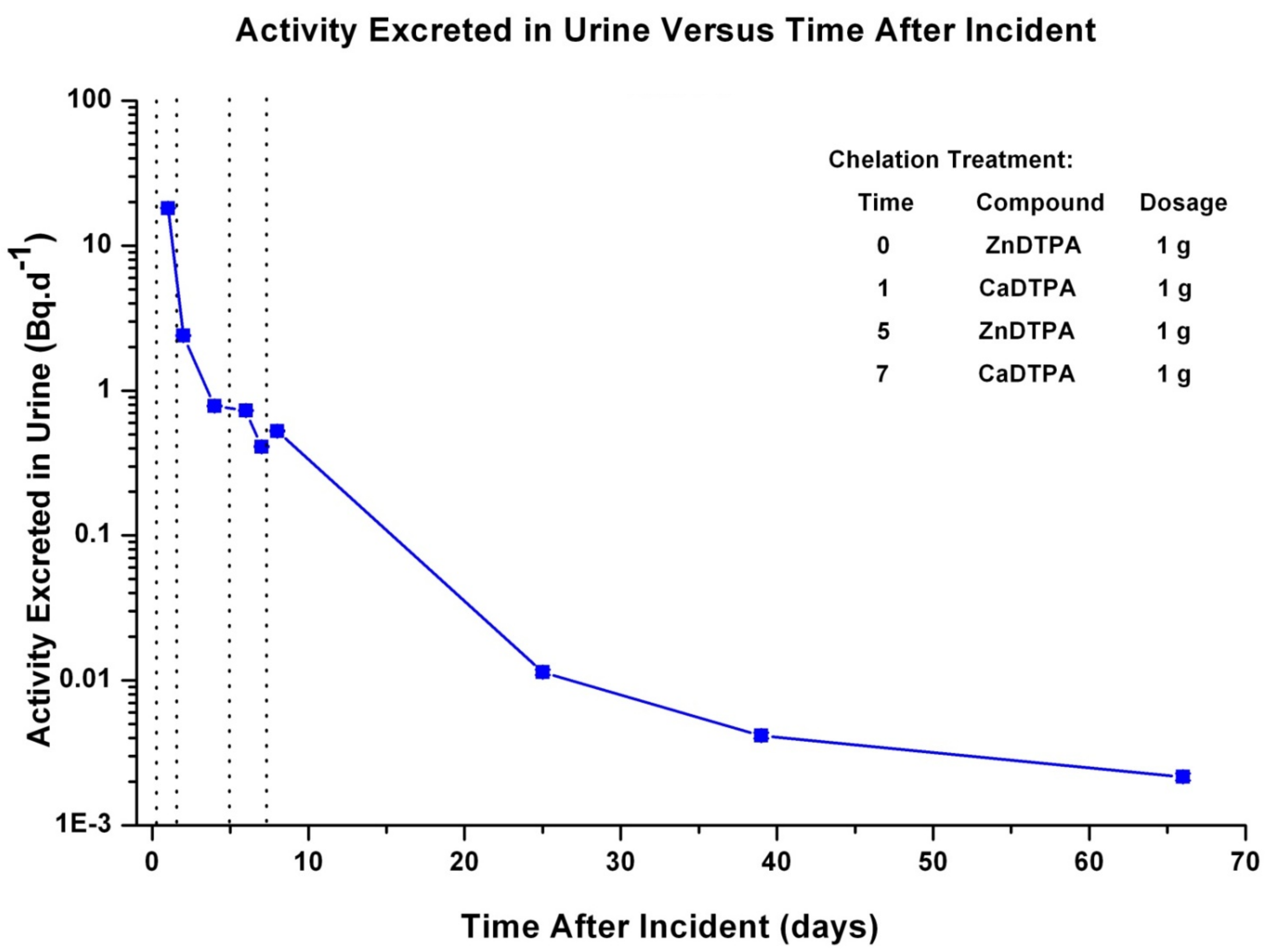
[2] With the further provision that the effective dose should not exceed 50 mSv in any single year. Additional restrictions apply to the occupational exposure of pregnant women, which is discussed in Section 5.3.3.

[3] In special circumstances, a higher value of effective dose could be allowed in a single year, provided that the average over 5 years does not exceed 1 mSv per year.

[4] The limitation on the effective dose provides sufficient protection for the skin against stochastic effects. An additional limit is needed for localised exposures in order to prevent deterministic effects (see paragraphs 173 and 194).

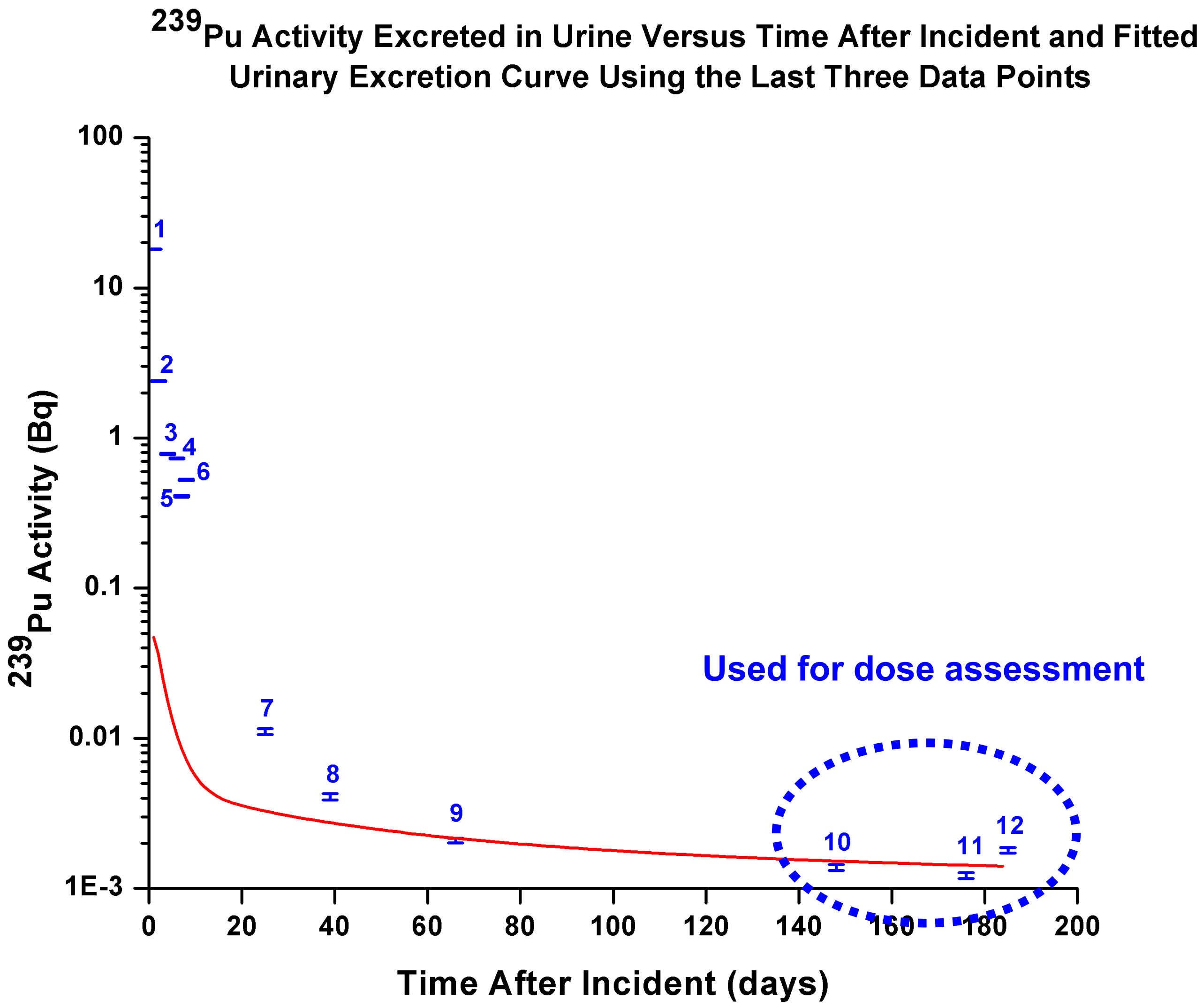
Limitations of the Biokinetic Models

A case of a wound contaminated with ^{239}Pu (4 Chelations)



A case of a wound contaminated with ^{239}Pu

(Dose Assessment)



Planned publications

Phantoms and radiations transport calculations

- Radiation Transport for Adult Phantoms (Adult SAFs)
- Pediatric Reference Computational Phantoms + SAFs
- Pregnant Female and Fetus Reference Computational Phantoms + SAFs

Internal dose coefficients

- Occupational Intakes of Radionuclides (OIR), Parts 1 - 5
- Internal Dose Coefficients for Members of the Public, Pts 1 & 2
- *In utero* Internal Dose Coefficients for Maternal Intakes
- Breast-feeding Infant Internal Dose Coefficients for Maternal Intakes

External dose conversion coefficients

- External Dose Coefficients for Members of the Public

Use of Effective Dose

SAF = Specific Absorbed Fraction

Occupational Intakes of Radionuclides (OIR)

OIR Part 1 (ICRP-130)

- Introduction
- Control of occupational exposures to radionuclides
- Biokinetic and dosimetric models
- Methods of individual and workplace monitoring
- Monitoring programmes
- General aspects of retrospective dose assessment
- Data to be provided for elements and radioisotopes

Occupational Intakes of Radionuclides (OIR)

OIR Part 2 (ICRP-134)
H, C, P, S, Ca, Fe, Co, Zn, Sr, Y, Zr, Nb, Mo, Tc

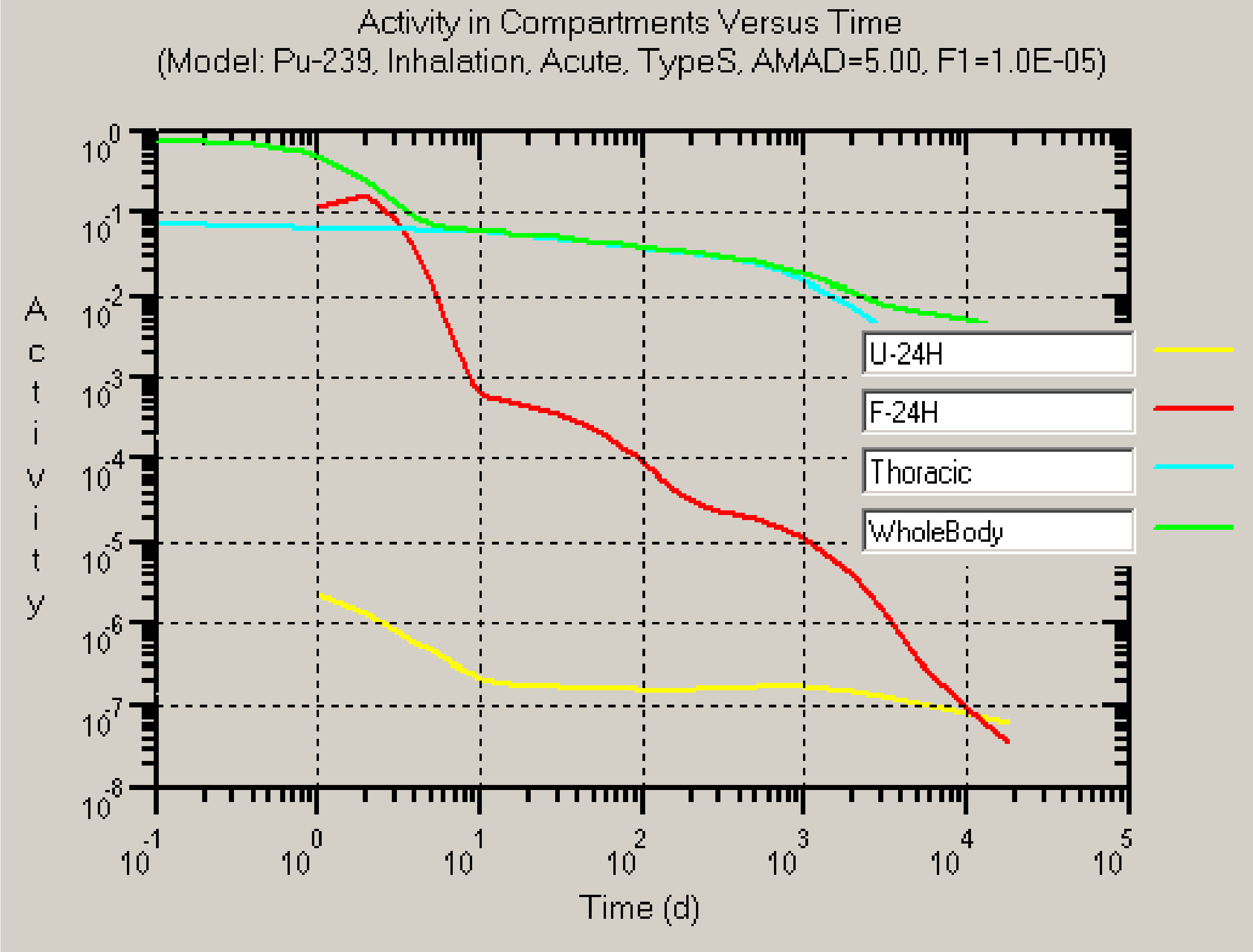
OIR Part 3 (ICRP-137)
Ru, Sb, Te, I, Cs, Ba, Ir, Pb, Bi, Po, Rn, Ra, Th, U

OIR Part 4 (ICRP-141)
Lanthanides and Actinides

OIR Part 5 (under revision)
F, Na, Mg, K, Mg, Ni, Se, Mo, Tc, Ag

Bioassay Interpretation

Intake Retention Fractions (IRF)
(activity in organs and excreta after a unit intake)



Intake Estimate:

$$I = \frac{\text{Measurement}}{\text{IRF}}$$

Internal Dose Estimate

- Committed Equivalent Dose

$$H_T(50) = I\,h_T(50)$$

- Committed Effective Dose

$$E(50) = I\,e(50)$$

where $h_T(50)$ and $e(50)$ are the committed equivalent dose in organ or tissue T per intake, and the committed effective dose per unit intake respectively (also known as dose coefficients).

THANKS!

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